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Global Biology Research Program

Program Plan

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M. B. Rambler, *Editor*
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GLOBAL BIOLOGY RESEARCH PROGRAM

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Reply to Attn of: EBT-3

Dear Colleague:

Global Biology is a new initiative within the Life Sciences Division of the Office of Space Science and Applications. The objective of this Program is to achieve a greater understanding of planetary biological processes as revealed by the interaction of the biota and the environment with a primary focus on global biogeochemical cycling.

This document is the product of the Global Biology Science Working Group which was convened to discuss and formulate NASA's role in the study of the biosphere. It is presented in the style and format of a NASA Program Plan. The report is not intended to be a comprehensive review of global biogeochemistry nor is it a solicitation of proposals in this area. Its purpose is to inform interested agencies and individuals of the rationale, scope, research strategy, and research priorities of NASA's Global Biology Research Program.

For further information on this program contact Dr. Mitchell B. Rambler, Program Manager.

A handwritten signature in black ink, appearing to read "Gerald A. Soffen".

Gerald A. Soffen
Director, Life Sciences Division

PREFACE

Earth is the anomalous planet in our solar system, the one place where both life and liquid water exist. The biotic and non-biotic components of the Earth's surface are involved in a complex interplay of inextricably linked physical, chemical, and biological processes. These processes are integrated over the entire globe by the land, atmosphere, oceans, and sediments, forming a system called the biosphere. It has been recognized that the production and removal of many of the biosphere's constituents are dominated by biological processes. The study of the influence of biology on global processes is herein referred to as GLOBAL BIOLOGY.

The provision of essential elements at rates and concentrations sufficient to support life is a function of biogeochemical cycling. Industrialized societies are drastically altering the biosphere, disturbing critical biogeochemical cycles, with little knowledge of the consequences of such actions. This situation makes the development of a scientific approach to global dynamics imminently important. However, this development has been hindered by the lack of multidimensional and multidisciplinary investigations of biospheric dynamics, and by the lack of sufficient technology to support such investigations.

Technological advances over the last five years have considerably strengthened the potential for a science of the biosphere. Satellite and aircraft remote sensing, coupled with sophisticated analytical instruments, provide important new tools for monitoring the extent, rate, and significance of changes in the biosphere. Computer systems can now store and process the prodigious amounts of data that remote sensing systems gather.

Most important, new theoretical models facilitate data integration, designate gaps in existing knowledge, and provide direction and focus for future research efforts, while reflecting current levels of understanding.

The NASA Life Sciences Division convened a series of workshops to develop a comprehensive program in global biology. These workshops, held in 1979, 1980, and 1981 (see appendix), focused on the manner in which biological processes influence major geochemical and atmospheric cycles. Given the complexity of the biosphere, it was recognized that an interdisciplinary approach is required to understand the influence of these biological processes on global dynamics. Leading scientists from a range of disciplines were brought together to identify, and to formulate a scientific rationale to answer, the major questions in biogeochemical cycling. Their work helped to define priority areas for research emphasis, and led to the establishment of a Global Biology Science Working Group that is responsible for developing a research strategy based on the workshop recommendations.

This document presents the work of the Global Biology Science Working Group. It includes a scientific rationale and prescribes research activities for developing an understanding of biospheric dynamics revealed by the interaction between the biota and the environment.

This report does not describe state-of-the-art global biogeochemistry. Rather, it outlines a preliminary research strategy to address the discipline's major unresolved scientific questions.

Members of the scientific community are invited to participate in the Global Biology Research Program. Instructions for submitting proposals are given in Section III.

The Global Biology Science Working Group consisted of Dr. Mitchell B. Rambler, Chairman, Program Manager; Dr. Berrien Moore, University of New Hampshire; Dr. Robert C. Harriss, Langley Research Center; Dr. Vytautas Klemas, University of Delaware, and Dr. Peter Vitousek, University of North Carolina.

EXECUTIVE SUMMARY

Life depends on the cycling of material through different energy states. This cycling provides essential elements at rates and concentrations that are sufficient to support life. Biological processes play a major role in transforming and transferring these components, but their significance has been recognized only recently. The biotic and non-biotic components of the Earth's surface are involved in biogeochemical cycling--a complex interplay of inextricably linked physical, chemical and biological processes. These processes are integrated over the entire globe by the atmosphere, oceans, and sediments, forming a system called the biosphere. To illustrate the multidisciplinary and multidimensional nature of biogeochemical cycling, consider the following examples: Biogenic gases modulate the atmosphere's composition and chemistry; products of biological processes affect sediment composition and chemistry; the reflectivity of vegetation affects radiative transfer, which in turn, influences atmospheric and oceanic processes.

A holistic, interdisciplinary approach to biospheric dynamics is required to understand the fundamental nature of the system that supports life on Earth. NASA's Global Biology Research Program is therefore dedicated to achieving a greater understanding of planetary biological processes as they are revealed in the interaction of the biota and its environment.

Within such a framework, the Global Biology Research Program requires a major modelling effort to integrate existing and developing data on biogeochemical cycling, global vegetation/biomass, land use changes, and atmospheric and oceanic

processes. Extensive field measurements are needed to provide crucial in situ data. The establishment of a stratified sampling program is needed to correlate effectively field and remote sensing data for global extrapolation. Important supporting tasks include laboratory investigations and instrument development.

The proposed research program initially calls for:

(1) identification of existing and developing data sets pertinent to biospheric modelling; and (2) development of a data network to provide access to georeferenced information and to allow continual assessment of the extent, rate, and significance of environmental changes.

There are four specific research objectives for the first ten years:

1. Establish a basis for assessing the major pathways and rates of exchange for carbon, nitrogen, sulfur and phosphorus moving into and out of terrestrial ecosystems.

The biogeochemical cycles of carbon (C), nitrogen (N), phosphorus (P), and sulfur (S) provide living organisms with most of the nutrients they require to sustain life. Changes in any, or all, of these cycles produce complex ripple effects that can extend throughout the entire biosphere. Unfortunately, our knowledge of the way these biogeochemical cycles relate to one another compares poorly even with our abbreviated understanding of the individual cycles themselves.

Existing data on the current state of the planet's vegetative cover, soil condition, and those chemical and biological processes dealing with nutrient

transport, must be evaluated before a program of new data acquisition is initiated. The evaluation will identify critical data gaps and thereby delineate research needs. A survey of existing research projects in other agencies will be included in the evaluation so that research activities can be coordinated and redundancy of effort can be eliminated. To gain a perspective of global biogeochemical cycles, regional scale studies will be initiated in those areas that are considered representative of the major ecosystems of the globe. The regional studies will then be incorporated into a stratified sampling plan that correlates ground-based measurements with aircraft and satellite data. This approach will allow investigators to extrapolate global scale dynamics from local processes.

2. Establish a basis for extrapolating local rates of anaerobic activities to biospheric effects, with particular attention on the role of reduced gases and their key oxidation products.

Biogenic gas fluxes of reduced gases directly influence and are influenced by atmospheric composition, and affect both climate and radiative transfer. Current evidence suggests that the concentration of reduced gases in the atmosphere is increasing. The ability of an ecosystem to generate reduced gases is controlled primarily by microbial activity, which varies with ecosystem type. Human activities have directly altered atmospheric composition by the release of fossil fuels. Moreover, changes in land use and cover have altered the distribution and extent of ecosystems, affecting biogenic gas fluxes and, in turn possibly affecting the natural balance of the biosphere.

Characterizing the natural baseline of biogenic atmospheric gas fluxes is needed, so that the nature and consequences of anthropogenic perturbations can be assessed and the influences of biological processes on the biosphere can be understood. There is also a clear need to establish a basis for extrapolating local rates of anaerobic activities to biospheric effects: in particular, the role of reduced gases, their key oxidation products, and their influence on biogeochemical cycles should be emphasized. This program element addresses the development of methods required to study the processes and rates by which reduced gases are generated.

3. Establish a basis for assessing the major pathways and rates of exchange for carbon, nitrogen, sulfur, and phosphorus moving into and out of the world's oceans.

Ocean productivity is controlled mainly by a supply of nutrients. It is, therefore, necessary to understand the physical, chemical, and biological factors which regulate the concentration of those nutrients. The rate of nutrient transfer from the land and the atmosphere to the ocean depends upon the complex metabolism of the land based biota. One way of linking terrestrial ecosystems to the oceans is by rivers. The biogeochemistry of streams and rivers is greatly affected by the character of the associated terrestrial ecosystems and is, therefore, sensitive to land use alterations within these systems.

The study of global biogeochemical cycles requires the characterization of the interactions between the land and the ocean, and the ocean and the atmosphere. In situ measurements of C, N, S, and P, will be performed

in rivers that communicate with coastal zones. Gas exchange into and out of the atmosphere, will be studied in areas of high and low ocean productivity. Regional and local scale studies will be correlated with satellite and aircraft remote sensing.

4. Develop mathematical models that accurately represent the dynamics of the global cycles of carbon, nitrogen, phosphorus and sulfur, including their interactions. Develop process-level mathematical models to explore key processes that control the dynamics of elemental interactions.

A science that chooses the Earth as its fundamental biogeophysical unit faces extraordinary scientific difficulties. However, the development of mathematical models that represent the global cycles of C, N, S, and P, can provide a mechanism for integrating ground-based and remote sensing data, while also reflecting our understanding of the systems involved. Initially, the modelling component will focus on simple causalities which affect the interactions of the major biogeochemical cycles of C, N, S, and P in a one year to a one hundred year time frame. Eventually, comprehensive models will be developed that incorporate key processes of elemental interactions, subsystem controls, and complex causalities in an expanded time frame. The more sophisticated models will address the state of biogeochemical cycles in the past, present and future.

The accuracy of biogeochemical models can be tested by correlating the predictions stated in the model with actual past events. Global biogeochemical models that are consistent with process level studies and broader biome scale dynamics can serve as test areas for

various assumptions and theories on both large and small scales. Models can be used to predict the extent and the consequences of human perturbations of the biosphere. The development of models that describe biogeochemical cycles will provide a framework for managing and protecting global resources.

In summary, the following items represent key elements and priority issues for research needed to satisfy the objectives stated above:

- 1) Existing data identification and development of a data network.
- 2) Biomass size and distribution.
- 3) Ecosystem areal extent and rates of change.
- 4) Atmospheric trace gas flux measurements and factors affecting magnitude.
- 5) Development of biogeochemical cycle models and elemental linkages.

This set of research objectives carries additional program corollaries, including the need to:

- ** Evaluate advanced remote sensors under development for quantitative surveys of global ecosystem properties.
- ** Set requirements for new remote sensing instruments and data analysis techniques for global ecosystem monitoring in:
 - i) survey mode: to provide data for calibrating and exercising models and updating data base.
 - ii) alarm mode: to provide near-real-time data to alert investigators to abnormally fast environmental degradation in selected regions of the world.
- ** Develop advanced data bases and data base management systems (DBMS) appropriate to the program.
- ** Establish a management structure and a community of interested investigators.

The overall approach required to answer these questions involves extrapolating regional scale studies to global scale processes. Recent developments in remote sensing technology offer tools by which detailed ground-based analyses can be expanded into a global perspective. Computer hardware and software developments provide the means to handle the prodigious amount of data that such an effort would generate. However, the inherent difficulty in studying the biosphere is in the multidisciplinary and multidimensional facets of biosphere dynamics. By building on the experience NASA has gained in managing and operating planetary studies, an integrated program in global biology can be implemented. The convergence of NASA technology and management experience on the study of global biogeochemical cycles places an understanding of the biosphere within our grasp.

I. INTRODUCTION

During the last decades of the 20th Century, human activity has greatly influenced the physical and chemical nature of the planet, by changing the composition of both the atmosphere and landscape. These changes, measurable in decadal time frames, are likely to have long term impacts on the future state of the biosphere. In fact, alteration of global biogeochemical cycles by human activity (Figure I.1, Table I.1) has already reached a critical stage: fluxes of individual cycles have begun to move outside their historical ranges (Figure I.2). The current concern over two major and widespread environmental problems--the increase in atmospheric carbon dioxide and the onset of acid rain--illustrates the urgency for quantitative answers to the questions raised by changes in the major biogeochemical cycles and their impact on global resources.

Despite the carbon cycle's critical role in the functioning of the biosphere, it is not well understood. Early models of the global carbon cycle suggested that observed patterns of fossil fuel-induced CO_2 buildup could be explained only if the terrestrial biota were a net sink for the added CO_2 (Bacastow and Keeling, 1973). The geochemists and atmospheric scientists who developed these models suggested that the rise in atmospheric CO_2 stimulated CO_2 fixation and storage by terrestrial plants. This conclusion troubled many terrestrial ecologists, because it is generally believed that the availability of essential nutrients, rather than CO_2 , limits terrestrial plant growth. Moreover,

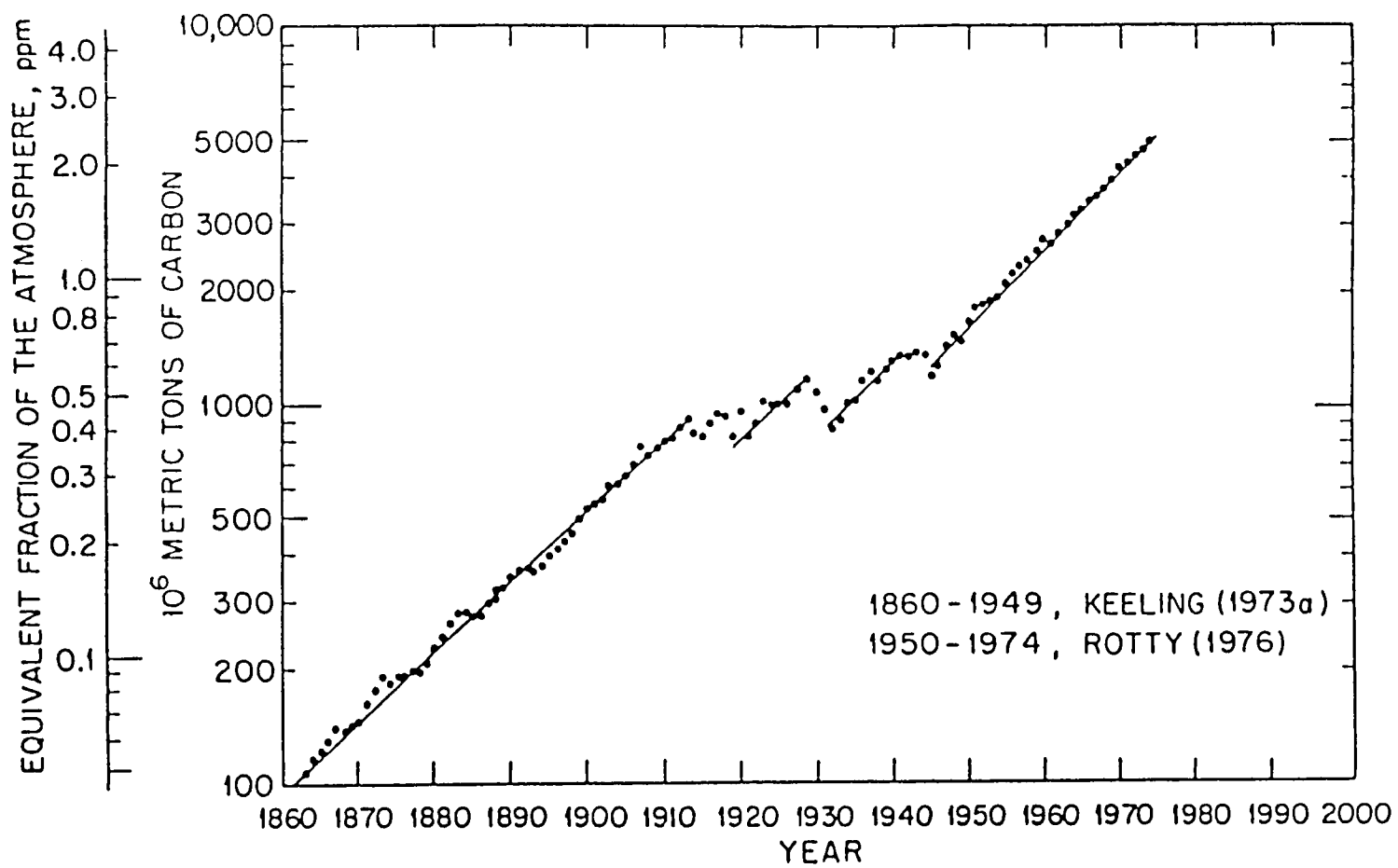


FIG. I.1. ANNUAL CO₂ PRODUCTION FROM FOSSIL FUELS AND CEMENT.

(from Baes et al., 1976)

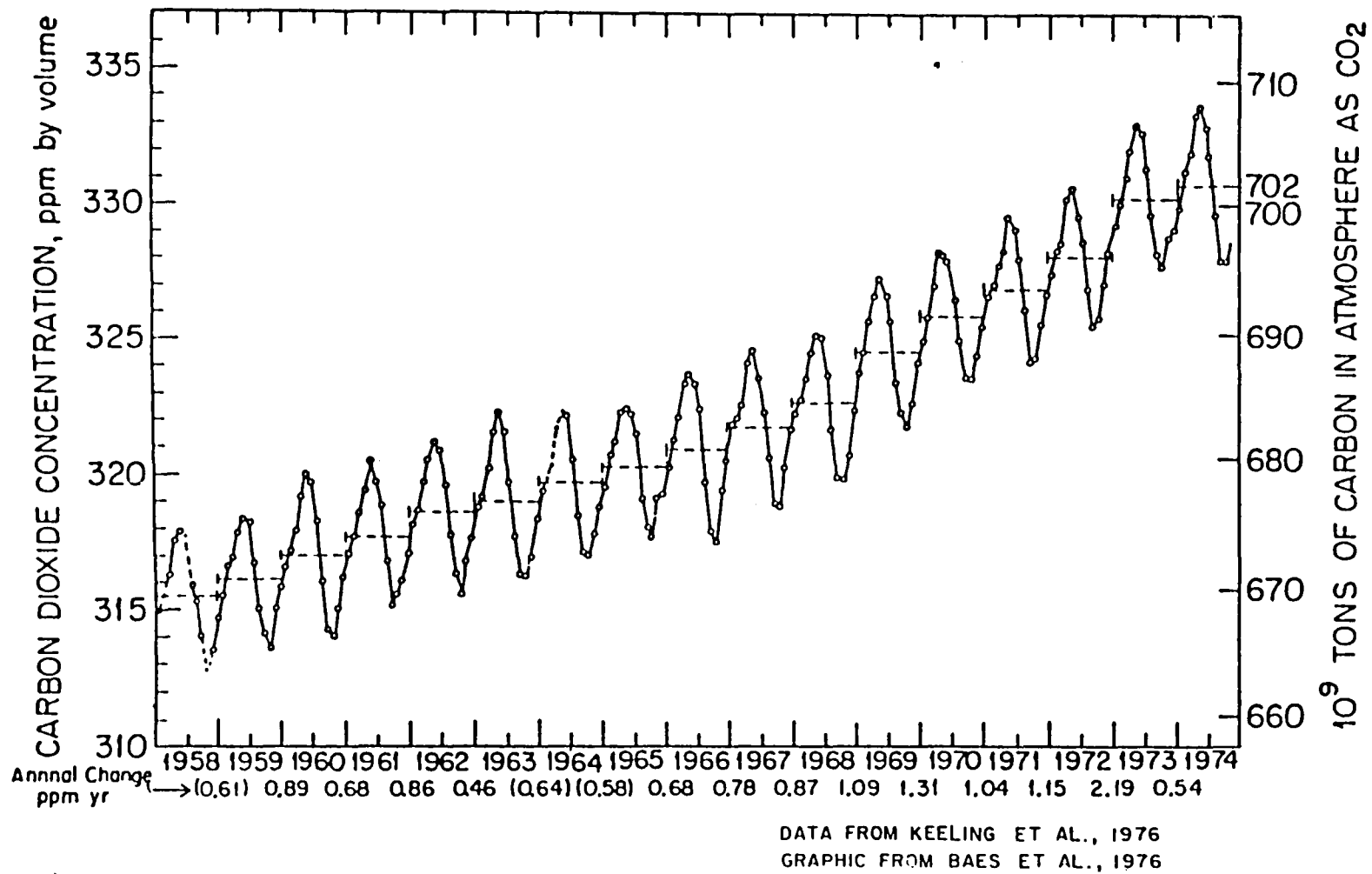


FIG. I.2. ATMOSPHERIC CO₂ CONCENTRATION AT MAUNA LOA OBSERVATORY.

TABLE I.1
(from Peterson, 1981)

<u>Nutrient Source</u>	<u>Reference</u>	<u>Nitrogen-N (form)</u>	<u>Phosphorus-P (form)</u>
Upwelling	Broecker 1974	314 (NO ₃ >)	46 (PO ₄ >)
Runoff	Broecker 1974		0.5 (PO ₄ >)
	Stumm 1973		1.8 (PO ₄ >)
	Emery et al. 1955	19 (total dissolved)	2.2 (total dissolved)
			12.0 (sediment P)
	Delwiche & Likens 1977	35 (total N)	0.7
	Soderlund & Svensson 1975	13.24 (total N)	
	McElroy 1976	20 (total N)	
	Sweeney et al. 1977	30 (total N)	
	NAS 1978	18 (total N)	
Precipitation on Ocean (Total Deposition)			
	Soderlund 1976	20-50 (NH ₄ >+NO ₃ >)	
	Soderlund & Svensson 1975	30-83 (NH ₄ >+NO ₃ >)	
	McElroy 1976	20 (NH ₄ >+NO ₃ >)	
	Sweeney et al 1977	15 (NH ₄ >+NO ₃ >)	
	NAS 1978	17-24 (NH ₄ >+NO ₃ >)	
	Delwiche & Likens 1977		4.0 (total P)
	Pierrou 1976		2.6-3.5 (total P)
	Emery et al. 1955	59 (NH ₄ >+NO ₃ >)	
Phosphate Mining			
	White & Reynolds 1974		
	1960-1974 avg.		5.0 (P)
	Stumm 1973		
	(1970 UN Yearbook value)		10.0 (P)
	Pierrou 1976		
	(1974 UN Yearbook value)		10.4 (P)

<u>Nutrient Source</u>	<u>Reference</u>	<u>Nitrogen-N (form)</u>	<u>Phosphorus-P (form)</u>
N Fertilizer			
	Delwiche & Likens 1977	40 (NO ₃ +NH ₄)	
	Soderlund & Svensson 1975	36	
	McElroy 1976	40	
	Sweeney et al. 1977	35	
	NAS 1978	49	
Fossil Fuel Emmissions			
	NAS 1978	21	
	Delwiche & Likens 1977	18 (NO _x)	0.5 (total P)
	Soderlund & Svensson 1975	19	
	McElroy 1976	40	
	Sweeney et al. 1977	15	
Plant Material Combustion			
	Delwiche & Likens	50	2.5 (total P)
	NAS 1978	10-200	
Sewage (4 billion people) (1)			
	Vollenweider 1968	15 (total N)	3 (total P)
Land Use Intensification (2)			
Oceanic N Fixation			
	references as for N fertilizer	30-130	
Oceanic Denitrification			
	references as for N fertilizer	90-120	

(1) assuming 2.18 g P/capita/day and 10.8 g N/capita day.

(2) estimated from the assumption that man may disturb 50% of the terrestrial area, increasing the phosphorus output by an average factor of about 5. For example, see Dillon and Kirchner 1975.

increased photosynthesis does not necessarily translate into increased carbon storage in vegetation and soils (Woodwell, et al, 1978). Most convincing, was the argument that the rate of deforestation worldwide was sufficient to reverse any trend toward net carbon storage on land.

Controversy is focused on the role of terrestrial ecosystems, where at least two factors govern the level of carbon storage. First, the alteration of the earth's surface by phenomena such as the conversion of forest to farmland, results in a net release of CO_2 to the atmosphere (Woodwell, et al, 1978; Moore et al., 1981; Olson et al., 1981; Houghton et al., 1982). Second, and more subtle, changes in biogeochemical cycles--carbon, nitrogen, phosphorus, and sulfur--may result in changes in net ecosystem production. Quantifying the changes in and the interactions of these cycles is needed because the non-carbon cycles provide the limiting nutrients in most terrestrial ecosystems (Melillo and Gosz, 1982).

Unfortunately, our knowledge of the way these biogeochemical cycles relate to one another compares poorly even with our abbreviated understanding of the individual cycles themselves. When humans burn fossil fuels, not only are large amounts of carbon released into the atmosphere, but also the input of nitrogen entering terrestrial ecosystems in bulk precipitation is raised. This rise in available nitrogen may stimulate both the fixation and storage of carbon in certain ecosystems; e.g., forest ecosystems. Conversely, wood harvests can reduce not only the carbon stock but also the nitrogen stock of forest ecosystems. When nitrogen leaves the forest in harvested material, erosion--accelerated by the harvest--carries off nitrogen-bearing soil. In addition, forest cutting can dramatically raise losses of inorganic nitrogen (principally in the form of nitrate) that is removed in solution by streams draining cutover areas. Wood harvests may also stimulate denitrification. As a consequence,

further understanding of either the nitrogen or the carbon cycle will require a clearer picture of the coupling that occurs between the two elements.

When dealing with the problems associated with carbon-nitrogen interaction in ocean dynamics, longer time scales than those evoked for land use/cover changes are required. Nitrogen is lost from the ocean by denitrification in upwelling systems at a rate of approximately 10^{14} g N yr⁻¹, enough to deplete the nitrogen reservoir (8×10^{17} g N, mainly NO₃⁻ in deep ocean) within 10^4 years. It is usually assumed that this loss of nitrogen and a similar loss associated with the incorporation of nitrogen into sediments is balanced by a combination of runoff from land, input from rain, and in situ fixation. More careful review suggests that these sources (at least at present) provide less than 10^{14} g N yr⁻¹. Very little of the nitrogen in rivers appears to reach the open ocean, because it accumulates primarily in estuarine and coastal sediments. There is no evidence for significant in situ marine fixation, even under conditions where nitrogen is a limiting nutrient. Moreover, several independent lines of reasoning suggest that the atmospheric contribution to oceanic fixed nitrogen is similarly small.

These considerations suggest that oceanic nutrients (at least nitrogen) are not in steady state. One must consider the possibility that nitrogen lost through denitrification is replaced primarily by episodic supply from land, particularly during times of advancing ice. Nitrogen stored in estuarine and coastal sediments during interglacial periods would be exported with the sediments to the open ocean. As the ice sheets advanced, the sediments would have eroded, exposing the stored nitrogen.

We can envisage episodes in which the supply of nitrogen to the ocean exceeds the loss of nitrogen from the ocean; and compensating intervals during which the system operates in the opposite direction, thereby maintaining an approximate balance

over long periods of time. One can argue that nutrients are transferred from the land to the ocean during times of advancing ice. This transfer would increase CO_2 fixation, which would cause the transfer of carbon from the atmosphere to the ocean to increase, resulting in a more productive ocean. These events would lead to a colder climate that would favor the advance of ice and the additional mobilization of nutrients. However, receding glaciers can cause positive feedback, where the supply of nitrogen from the land to the ocean would be decreased. Thus atmospheric CO_2 would increase, accelerating the rate of warming. Broecker (1979) has advanced a similar argument for the long term role of phosphorus in the ocean.

Phosphorus is essential for plant growth, yet it is frequently in short supply relative to carbon and nitrogen. Phosphorus is nonvolatile, a quality that restricts its role in atmospheric chemistry. Its relative insolubility limits its availability to organisms in soils, rivers, and oceans. In the absence of human activity, these characteristics limit the element's role in global biogeochemical cycling. However, human activity has altered the availability of phosphorus in direct and in indirect ways. The application of phosphorus fertilizer is a direct perturbation (Table I.1), but subtler alterations of the phosphorus cycle may influence the dynamics of other cycles. Fire, as either a natural phenomenon or as a management technique, may increase the available stocks of phosphorus, since oxidation of plant litter transforms organically bound phosphorus into "more available" forms (Walker, 1976). Increased levels of available phosphorus can, in turn, raise the rate of nitrogen mineralization in soils (Melillo, 1977; Vitousek, personal communication; Reiners, personal communication). In addition, there is a possible coupling of carbon and nitrogen through fire. Rapid oxidation of the carbon in litter with a high C:N ratio reduces the amount of nitrogen that can be immobilized by microorganisms during decay, thereby increasing the amount of nitrogen available to plants.

Sulfur plays an equally important role in maintaining biological systems, since it is an essential nutrient for all plants, bacteria, and animals. In fact, sulfur is a limiting nutrient in the Canadian grain belt (Saskatchewan) (Armentano and Ralston, 1980). However, sulfur is no longer a limiting nutrient in the American grain belt since it is provided to this region from industrial effluents. In addition, sulfur has great impact on the carbon and energy cycles in marine ecosystems because it is so widely available in seawater as sulfate.

The sulfur cycle is assuming increasing importance on a global scale, as the full impact of acid rain and atmospheric sulfur pollution becomes known. Indirect calculations suggest that emissions of gaseous sulfur to the atmosphere from fossil fuel combustion are already on the same order of magnitude as releases from natural systems (Peterson, personal communication). High rates of sulfate reduction and periodic tidal exposure of sulfur to the atmosphere combine to make coastal wetlands prime sources of atmospheric sulfur. Clearly, the biogenic sulfur fluxes are large, yet few direct measurements are available for them, and the requisite techniques for these measurements are still uncertain. Consequently, we lack the data needed for a global estimate.

Anthropogenic effects on global biogeochemistry are large enough to raise certain practical questions, for which no clear answers can be provided.

- ** What is the present state of the major biogeochemical cycles?
- ** What was their state prior to anthropogenic perturbations?
- ** What future states are likely?
- ** What are the likely results of these future states?
- ** What can be done to control these cycles?

II. RESEARCH ISSUES

In this chapter, the major research issue-areas of the Global Biology Research Program are described, and priorities for the first five years are presented. The specific research tasks associated with each aspect are discussed in the next chapter.

There are four major research issue-areas in the Global Biology Research Program:

1. The major pathways and rates of exchange of carbon, nitrogen, sulfur, and phosphorus to and from terrestrial ecosystems.
2. Anerobic processes and the associated terrestrial sources of trace gases.
3. The major biogeochemical fluxes to and from the world's oceans that are directly modulated by biological processes.
4. Integration of biogeochemical flux into macro-scale global models and meso-scale process models.

This collection carries additional program elements including the need to:

- ** Evaluate advanced remote sensors being developed for quantitative surveys of global ecosystem properties.
- ** Define requirements for new remote sensing instruments and data analysis techniques for global ecosystem monitoring in:
 - i) survey mode: to provide data for calibrating and exercising models and updating data base.
 - ii) alarm mode: to provide near-real-time data to alert investigators to abnormally rapid degradation of the environment in some critical area of the world.
- ** Develop advanced data bases and data base management systems (DBMS) appropriate to the program.
- ** Establish a management structure and a community of interested investigators.

II.1 Biogeochemical Cycles and Terrestrial Ecosystems.

There are two distinct subsystems of the terrestrial biosphere and each requires its own approach when attempting to estimate the exchange of C, N, S, and P. These two subsystems are:

1. Those that have not been directly disturbed by humans.
2. Those that have been directly disturbed by humans.

Initially, the Global Biology Research Program will focus on disturbances in terrestrial ecosystems (e.g., tropical deforestation). It is the response of the biosphere to disturbance which will lend the greatest insight into the mechanisms that provide stability. In part, human disturbance of the biogeochemical cycles provides an ongoing experiment at the global level. As such, it is important to monitor the various perturbations that constitute forcing functions in the experiment and the characteristics of the response of the biosphere to these perturbations. Hence the Program will not initially attempt to improve measurement of biogeochemical exchanges in undisturbed terrestrial systems. However, the value of improved estimates of primary production or nutrient exchange in undisturbed regions should not be underestimated, and these data will be pursued as the Program develops.

Three major components are needed to form the basis for determining the fluxes of C, N, S, and P to and from disturbed terrestrial ecosystems:

1. Good measurements of the rates of natural and human-caused disturbances.

2. Accurate transfer functions relating changes in C, N, S, and P stocks in terrestrial ecosystems to the magnitude and occurrence of disturbance.
3. The controls of the pathways and the characteristics of the interactions involved in C, N, S, and P gains and losses in terrestrial ecosystems.

These three research components are clearly related and will require continuous communication among the investigators. Nonetheless, they differ substantially in the techniques needed to address them and in the level of biological organization with which they are concerned. Therefore, they are discussed separately.

II.1.1 Rates of Disturbance and Land Use Change.

Satellite sensors collect reflected and emitted energy across several octaves of the electromagnetic spectrum (0.2 μm to > 1 m wavelengths) and convert the energy into a series of signals that can be used to produce many different images of the earth's surface. Such images have been used effectively to determine the distribution of various types of vegetation and to infer other details of plant cover. Effective use of this type of information to measure the area and other more subtle characteristics of plant cover will require substantial collateral information, including occasional aerial photography and ground-truth measurements. However, the usefulness of satellite imagery to detect changes in land use remains unchallenged. The questions pertaining to satellite data involve details of the approach and of the level of accuracy possible.

Measuring change in the amount of biomass held in the vegetation and soils of the earth requires two different kinds of information. One is the knowledge of the change in area of different ecosystems; and the other is data on changes in biomass

densities within an ecosystem. The first of these, measurement of the change in area, is obtained readily from analysis of satellite imagery. Areas are defined by the smallest element of the image, the picture element or "pixel." The error inherent in defining the edge of a pixel, and hence in calculating its area is small. It is approximately 2.5% for a 100 hectare (ha) scene and decreases with the square power as the area increases (Bartlett and Klemas, 1980).

Acquiring the second type of requisite information--the amount of biomass per unit area in a given system and the change in this biomass following disturbance--could be more difficult. This step has two components: the biomass in vegetation and the biomass in soils. Each is a major research topic in itself, the latter being the more difficult. Successional changes are important because they define the rate of storage of biomass in secondary forests. In well-known vegetation zones, such as the temperate zone or boreal forests, the major stages of succession are known and can be identified in the field. Identification of these stages on satellite imagery may be possible but will require a substantial effort. In poorly characterized vegetation zones, such as tropical forests, more field experience is necessary before successional stages can be identified. Their distinction on satellite imagery is not immediately possible. The discussion of changes in biomass densities is continued in the next section on transfer functions.

Fortunately, reasonable information describing biomass and soil changes following a variety of disturbances in many ecosystems is available (Bolin, 1977; Likens, et al, 1977; Vitousek, 1982a, 1982b), although there remains major ecological uncertainty about the tropical zone. Our ability to estimate the net flux of important elements, such as carbon, to or from terrestrial ecosystems is limited primarily by uncertainty over the magnitudes of natural disturbance, land clearing, and vegetation regrowth in many regions of the world. While

information on land use for much of the industrialized world is relatively good (e.g., Delcourt and Harris 1980), the information available for the tropics is of mixed quality, and past data from the primary data source, the FAO statistics, has been notably unreliable.

It must be stressed that the uncertainty in the literature about biomass estimates per unit area is far less uncertain than the estimates of disturbance rates. Recent work by Brown and Lugo (1980) produced estimates of vegetation densities for tropical systems that are 50-75% of those offered by Whittaker and Likens (1975). The estimates of Brown and Lugo are probably a minimum value, and those of Whittaker and Likens a maximum; the range between recent estimates of disturbance rates by Norman Myers and FAO differ by over 500% (Houghton et al., 1983). In any event, direct measurement by remote sensing of the rates of disturbance in selected regions would be an enormously valuable contribution to our understanding of large-scale biotic alteration, and hence to our knowledge of one of the key perturbations in the biogeochemical cycles.

Forests represent a rapidly disappearing resource essential to economic and social development. Consequently, the rate of loss of our forest resources holds important implications for our understanding of global C, N, P, and S cycles, as well as to our ability to conserve these resources.

II.1.2 Development of Transfer Functions.

When a terrestrial ecosystem is subjected to destructive disturbance (defined as "the destruction of living organisms"; Grime, 1979) both organic matter and nutrients are lost to streamwater and/or to the atmosphere. These losses are caused by a variety of factors, including higher soil temperatures and moisture contents, faster decomposition, lower primary production and plant nutrient uptake, and increased erosion (Likens, et al,

1977; Bormann and Likens, 1979; Vitousek and Reiners, 1975; Vitousek 1982b).

When disturbance is followed immediately by secondary succession (the reestablishment of vegetation and nutrient cycles), organic matter and nutrient levels accumulate on site (Switzer and Nelson, 1972; Marks, 1974; Gorham, et al, 1979). Material is added from the atmosphere by photosynthesis, nitrogen fixation, atmospheric precipitation, and rock weathering. When land is converted to agricultural or residential use, C, N, S, and P levels continue to decline for many years (Van Veen and Paul, 1981; Voroney et al., 1981). More than half of the carbon and nitrogen present in native prairie or forest can be lost during the development of agricultural land. Secondary succession represents a transient decrease in standing state and is followed by regeneration of former levels of biomass and nutrients while the changes that occur following land clearing represent progressive changes to a new, lower equilibrium state (Bolin, 1977; Gorham, et al, 1979). Consequently, the total nutrient and biomass content of an ecosystem or vegetation class varies with both the initial ecosystem type and the time elapsed since it's disturbance.

Transfer functions which describe the changes in elemental content of disturbed systems are essential to the type of evaluation envisioned in the Global Biology Research Program. A considerable amount of data for organic carbon, in various ecosystems and stages of succession following disturbance, is presently available in the literature, and several are already incorporated into models (Moore et al., 1982). Agricultural experiment stations provide much of this information, including long-term records for certain areas of the tropics. However, the information available for other elements is less substantial. Yet, large amounts of nitrogen are lost from terrestrial systems following deforestation or land conversion to agriculture (Nye and Greenland, 1964; Folster et al., 1976,

Bormann and Likens, 1979). Losses of S and P are generally less than nitrogen losses (Likens, et al, 1977). Unfortunately, no detailed data base exists for these elements that is comparable to the data on carbon.

II.1.3 Control of C, N, S, and P Cycles and Interactions.

While the first component involves detailed studies of land use and the second component involves careful inventories of biomass and nutrient stocks, the third component requires process-level studies of the transformations and interactions of the C, N, S, and P cycles. The fundamental question addressed is "what controls the C, N, S, and P balances of terrestrial ecosystems?"

Present information suggests that, unlike marine systems, other elements in terrestrial systems may not maintain a fixed stoichiometric relationship with carbon (Vitousek, 1982a; Melillo and Gosz, 1982). Developing an understanding of stoichiometric variability and its causes is an important research issue of the development of transfer functions and their associated control characteristics.

II.2 Anaerobic Processes and Trace Gases.

The atmosphere contains abundant oxygen without which life, as we know it, would not exist. The transition from a reducing atmosphere to an oxidizing atmosphere, which occurred early in earth's history, was mediated by photosynthetic processes and set the stage for the evolution of metazoan life. Metabolic requirements of metazoans demand significant amounts of energy, that is supplied from the highly efficient metabolic oxidation of organic carbon compounds. Despite the fact that anaerobic metabolism is less efficient than aerobic, anaerobic organisms carry out many essential biospheric processes.

The anaerobic processes of microbial organisms in waters, wet soils, muds and sedimentary deposits of bays, lakes, estuaries, ponds and rivers are responsible for a significant flux of trace gases to the atmosphere. On a global scale, the reduced gases in the atmosphere (CH_3Cl , H_2S , CS_2 , etc. and their oxidation products, CO and SO_2) are important to the net radiation balance of the planet, the global climate, and to total primary productivity. In addition, anaerobic processes are of major importance to the accumulation and weathering of mineral deposits. Such deposits comprise vital resources for modern technology and represent an essential part of the recycling of the chemical elements necessary for life. Consequently, the biotic modulation of these trace gases holds important implications for the productive capacity of the Earth's biological systems. In this light, the Global Biology Research Program will attempt to expand our collective understanding of the complex linkages among the biosphere, atmospheric chemistry, and climate, that are mediated by microbial activity. Understanding the complexity of these linkages represents one of the major scientific challenges of this decade.

Although anaerobic processes and trace gases are directly related (for reduced gases) or indirectly related (for oxidation products), the program plan will discuss them separately. This distinction is an organizational device, and is representative of the distinct scientific disciplines that work within these issues: the anaerobic processes will tend to be within the focus of the microbial ecologist, while trace gases will often be within the purview of the atmospheric scientist.

II.2.1 Anaerobic Processes: The Research Issues.

Most studies of microbes have been carried out in laboratories on populations of single species. We know little about these processes under natural conditions. However, microbes exist in complex communities in the biosphere, and their activities and

the rates at which they transform chemical compounds depend on many factors--including the abundance and activities of other organisms. Classical methods of studying microbial activity have focused on single species physiology by isolating factors that influence biochemical processes. This approach has failed to describe natural conditions, where microorganisms interact with each other and with their environment. Consequently, data obtained using classical methods is not readily adaptable to models at an ecosystem or global level.

For example, recent studies in anaerobic sediments show that energy is used more efficiently by micro-colonies of heterogeneous microbes than by populations of single species. Certain bacteria that require anaerobic conditions live in microhabitats protected by the activity of oxygen-using bacteria. These community interactions reduce the usefulness of past data collections for community and ecosystem level study. The complex interactions among organisms in a microbial colony apparently increase the efficiency of material and energy transfers. The high degree of biotic modulation and the complexity of the interactions make these investigations both difficult and critical.

Microbial activity is not closely related to the total abundance or biomass. In any gram of soil there may be a billion microbial cells, most of which are inactive at any time. In a general sense, a healthy ecosystem requires the presence of sufficient numbers and species of microbes to carry out essential chemical processes. Yet it is often the microclimatic conditions that determine whether a particular process occurs. Consequently, new methods are needed to describe the actual and potential activity of a community of microbes.

Although there are many broad research issues in microbial ecology, the Global Biology Research Program will focus initially on specific tasks, which are discussed in Section III.2.1. The

general theme governing microbiological research for the program is that the research undertaken must contribute to the integration of transfer functions with habitat data; improving, by an order of magnitude, present estimates of major biogeochemical fluxes associated with microbial activities. This research will include methods to (1) refine estimates of the transfer of reduced gases from the biosphere to the atmosphere, and (2) quantify decomposition processes that influence rates of nutrient transfer between ecosystems. Further, these research efforts should be designed to provide insight into the effects of human-induced disturbances of terrestrial ecosystems on atmospheric chemistry and global productivity.

II.2.2 Trace Gases: The Research Issues.

Trace gases of predominately biogenic origin, such as CH_4 , N_2O , NH_3 , CH_3Cl , and others, are sensitive indicators of biosphere-atmosphere interactions. Quantitative measurements of biogenic gases provide critical information necessary to biospheric modelling such as:

- ** An index of large-scale (ecosystem) metabolic processes which respond to, and perhaps, modulate climate.
- ** An index of potential future directions in climate change.
- ** A measure of potential ecosystem resistance/resilience to environmental change.

The research issues involving trace gases in the C, N, and S cycles (the P cycle has no known natural gaseous species of importance) can be generally separated into two categories with respect to research issues-- (1) gases where measurement capabilities exist to address a number of urgent scientific

issues requiring both concentration and flux determinations (eg. CO_2 , CH_3Cl , CO , CH_4 , and N_2O); and (2) gases where measurement capabilities are satisfactory for ambient concentration measurements under most conditions but not satisfactory for flux determinations (eg. NH_3 , NO , NO_2 , H_2S , COS , and DMS). All of the biogenic sources of C, N, and S atmospheric gas species are of potential importance to global biogeochemical cycles (see, for examples--Bolin and Cook, 1982; NAS, 1981; Botkin, 1982: See Appendix). The following paragraphs briefly highlight some specific high priority research issues related to improving our understanding of biosphere-atmosphere interactions.

II.2.2.1 Carbon Monoxide.

Comprehensive reviews of existing data describing mechanisms and rates of transfer for tropospheric carbon monoxide have been published by Seiler (1974) and Logan et al. (1981). Examination of estimated carbon monoxide source strengths (Table II.2.1) reveals few data and many heroic extrapolations. The ratio of minimum to maximum source strength estimates, used as an index of uncertainty, provides a ranking system for sources of CO . From highest to lowest they are: soil uptake, carbon monoxide production from vegetation and vegetation-derived nonmethane hydrocarbons, biomass burning, and methane oxidation. The only source strength which is fairly well known is that of carbon monoxide production by fossil fuel combustion.

The destruction rate of carbon monoxide at the Earth's surface might be determined by employing the technology used to measure ozone deposition directly (Lenschow, 1981). A carefully designed program of carbon monoxide deposition measurements should be initiated for major global ecosystems.

II.2.2.2 Methane.

Current understanding of the distribution, sources, and sinks of methane in the tropospheric boundary layer can be summarized as follows:

- ** The tropospheric concentration of methane is approximately 1.65 ppmv (Heidt and Ehhalt, 1980); values greater than 2 ppmv have been commonly observed in urban atmospheres and in the vicinity of natural gas fields (Scranton et al., 1980); Dianov-Klokov et al., 1977).
- ** A 0.1 ppmv interhemispheric gradient in methane concentration has been measured with higher values in the Northern Hemisphere. The concentration gradient may be due to the spatial distribution of sources and/or changes in the concentration of other atmospheric gases such as CO or the OH radical, which influence the photochemical destruction rate of methane.
- ** Several lines of evidence suggest that tropospheric concentrations of methane are increasing. Graedel and McRae (1980) reported an increase in methane over the past decade at a suburban location in New Jersey. Rasmussen and Khalil (1981) observed a 1.9 percent per year increase in atmospheric methane concentration during a 2-year (1979-1980) monitoring program at Cape Mears, Oregon. The latter data set also exhibits considerable seasonal variability which is unexplained at present.

** Existing estimates of global sources of methane to the troposphere are highly uncertain. Recent studies on wetland sources (rice paddies, swamps, river floodplains, etc.) demonstrate a 100-fold variation in emission rates of methane related to both natural and anthropogenic factors (Table II.2.2 from Harriss and Sebachner, 1981; Cicerone and Shetter, 1981.)

It appears reasonable to expect that a more extensive program of flux measurements will provide the basis for a reasonable quantitative estimate of the role of wetlands as a global source of atmospheric methane. Other sources (e.g., combustion, animals, etc.) also require quantification. In fact, greater understanding of the sources of global methane is a prerequisite to any evaluation of the impacts of changes in global tropospheric methane on the carbon monoxide cycle.

The concentration and distribution of methane in the troposphere is relatively well known. Yet, the global sources of CH_4 are presently speculative; microbial fermentation in wetland ecosystems and enteric fermentation in certain mammals are documented sources, but global flux measurements are based on the extrapolation of a few limited measurements. Evidence suggests that the concentration of atmospheric methane is increasing; however, anthropogenic activities are significantly altering the extent of coastal and freshwater wetland ecosystems thought to be major sources of CH_4 . Destruction of swamps and marshes is well documented on a global basis. Consequently, the major gap in methane data is the lack of quantitative measurements of its terrestrial flux and lack of information concerning its involvement in anaerobic processes.

Table II.2.1

Global CO Budget (10^{12} gm CO yr⁻¹)

	Total	Northern Hemisphere	Southern Hemisphere
Sources			
Fossil fuel use	450	425	25
	(400-1000)		
Oxidation of anthropogenic hydrocarbons	90	85	5
	(0-180)		
Oxidation of natural hydrocarbons	500	380	180
	(280-1200)		
Emissions by plants	130	90	40
	(50-200)		
Wood used as fuel	51	33	17
	(25-150)		
Forest Wildfires	25	22	3
	(10-50)		
Forest clearing	380	260	120
	(200-800)		
Savanna burning	200	100	100
	(100-400)		
Ocean	40	13	27
CH oxidation	810	405	405
	(400-1000)		
Total	(1500-4000)		
Sinks			
Soil uptake	250	210	40
Photochemistry	3170	1890	1280
	(1600-4000)		
Total	3420	2100	1320

From Logan et al. (1981)

Table II.2.2 Comparison of Measured Methane Fluxes from
Freshwater Wetlands

Site	Flux ($\text{g CH}_4 \text{ m}^{-2} \text{ day}^{-1}$)**	Ref.*
Michigan Swamp	0.52	1
Michigan farm ponds	0.52	1
Rice Paddy (open water)	0.004	2
Rice plants (unfertilized)	0.032 0.032	2 2
Rice plants (fertilized)	0.15	2
Virginia swamp	0.008	3
S.C. cypress swamp	0.01	4
Georgia cypress swamp	0.09	4
Florida cypress swamp (fertilized)	0.97	4
Florida cypress swamp	0.067	4

*References:

- 1 Baker-Blocker et al. (1977)
- 2 Cicerone and Shetter (1981)
- 3 Harriss et al. (1981)

**All flux measurements used for this comparison
were made in the soil temperature range 20-29 C.

II.2.2.3. Ammonia.

It is hypothesized that atmospheric ammonia is controlled by both natural and anthropogenic sources (Dawson, 1977; Denmead, et al, 1974). Estimates of both specific source strengths and of global fluxes are extremely limited (eg. see reviews by NASA, 1979). A main reason for such a poor state of knowledge on the biogeochemical cycle of ammonia has been a paucity of measurement techniques and, consequently, a lack of high quality data for either atmospheric concentrations or fluxes. However, recent advances in measurement techniques (McClenny and Bennett, 1980; Hoell, et al 1980) offer an opportunity to develop new research initiatives on the sources and sinks of atmospheric ammonia and associated chemical species.

Ammonia is a particularly important atmospheric gas because its properties as a base modulate the acidity of rain. In addition, the dry deposition of ammonia and the wet deposition of ammonium ion may be important sources of nitrogen to certain forests growing on nitrogen deficient soils (Denmead, et al, 1976). Top priority should be placed on the development of flux measurement techniques to define the biogenic sources of atmospheric ammonia as well as the dry deposition of atmospheric ammonia to ecosystems. A limited effort on studies of temporal variability of ambient ammonia concentrations in well characterized ecosystems (eg. Hubbard Brook), coordinated with measurements of additional C, N, S, and P species, will also be encouraged. It is very important to define linkages among biogeochemical cycles of these critical nutrients.

II.2.2.4. Nitrous Oxide.

The limited data available suggest that global tropospheric nitrous oxide is increasing (Weiss, 1981). N_2O is a principle source of the stratospheric nitrogen oxides which modulate the

ozone layer and, consequently, affect the amount of biologically harmful UV radiation reaching the surface of the Earth. Human impacts on the N_2O budget result primarily from the use of fertilizer and from combustion processes which enhance emissions to the atmosphere (Crutzen, 1974; Weiss and Craig, 1976; McElroy et al, 1977). Nitrous oxide is also an atmospheric "greenhouse gas"; increasing tropospheric concentrations will contribute to a warming of the Earth's surface (Hansen et al, 1981).

Extensive research is underway on biogenic sources of N_2O (Delwiche, 1978; Elkins et al, 1978). Results to date show that terrestrial sources of N_2O are highly variable in time and space. An aggressive program of field studies will be conducted in major biomass regions of the world to quantitatively assess N_2O source strengths, with particular emphasis on human impacts. Similar studies are needed on NO and NO_2 as techniques for measuring these species improve.

II.2.2.5. Methyl Chloride.

The important gases such as O_2 , CO_2 , N_2O , CH_4 , and CH_3Cl , are present in the atmosphere as a result of active biological processes. Considerable progress has been made in understanding the major biological cycles--the carbon cycle and the nitrogen cycle. However, the cycles of trace gases such as CH_4 , N_2O , and the halogens have only been studied recently (McConnel, et al, 1974). Even though the cycles of atmospheric halogens have received a great deal of attention in recent years (NAS, 1976; NASA, 1977, 1979; Logan, et al, 1978; Yung, et al, 1980; Cicerone, 1981), the biological aspects of halogen cycling have not been understood. It is imperative that investigations are conducted so that the biological mechanism by which atmospheric halogens are produced and the source strength of such processes can be understood. In recent years, there has been considerable concern that chlorine, associated with anthropogenic origin, may cause permanent damage to the ozone layer in the stratosphere

(Molina and Rowland, 1974; McElroy, et al, 1974; Cicerone, et al, 1975; Wofsy, et al, 1975; NAS, 1976; NASA, 1977; Crutzen, et al, 1978; NASA, 1979). To assess properly the impact of anthropogenic perturbation, we must first determine what is the background chlorine concentration in the absence of perturbation, and what are the other processes controlling the abundance of O_3 in the stratosphere. An analysis of the major sources of stratospheric chlorine indicates that CH_3Cl is the most important, accounting for more than 30% of the total chlorine (approximately 2 ppb) in the stratosphere today.

A quantitative evaluation of the various schemes known today for the distinction of O_3 is necessary to gain some understanding of the relative importance of chlorine to ozone chemistry. One atmospheric model (Yung, et al, 1980) indicates that chlorine accounts for 15% of atmospheric O_3 destruction, and that CH_3Cl accounts for 30% of the total chlorine budget. Hence, the impact of CH_3Cl on O_3 is 5%. If the concentration of CH_3Cl in the atmosphere were to double (because of natural or anthropogenic perturbation), the associated decrease of O_3 would be 5%. It is important to stress that the 5% change in the optical depth of the ozone (stated above) translates into a more significant transmittance of UV radiation--which is the ultimate source of concern. An understanding of CH_3Cl production by natural sources is, therefore, vital to the construction of an atmospheric halogen budget and to the assessment of its impact on stratospheric ozone.

II.3 Biogeochemical Cycles and the Oceans.

The Global Biology Research Program will include research to improve our understanding of fundamental biological processes and the associated data relevant to oceanic biogeochemical cycling, thereby establishing a basis for assessing the major pathways and rates of exchange of carbon,

nitrogen, sulfur, and phosphorus to and from the world's oceans.

The rate of nutrient transfer from the land and the atmosphere to the ocean depends upon the complex metabolism of the land based biosphere--in both its aerobic and anaerobic functions--and upon the interplay of atmospheric chemistry and terrestrial sources and sinks. The terrestrial system is complex and poorly quantified on a global scale. The research issues in Sections II.1 and II.2, discussed, in part, the nature of these terrestrial uncertainties.

One of the ways that terrestrial ecosystems are linked to the oceans is by rivers. The surface waters draining each continent play a key role in transporting and processing carbon and nutrients. The biogeochemistry of streams and rivers is greatly affected by the character of the associated terrestrial ecosystems and is sensitive to alterations in land use within these systems. Further, the productivity and rates of nutrient cycling in the rivers, downstream lakes, estuaries and oceans are sensitive to the levels of carbon and available nutrients that these waters carry.

Dramatic and abundant evidence illustrates the responses of lakes, rivers, estuaries, and coastal oceans to changes in nutrient loading that result from land use alterations. For the most part, the changes have accelerated the cycling of nitrogen, phosphorus and sulfur. This accelerated cycling leads to increases in both primary productivity and decomposition in aquatic systems (eutrophication), with concomitant increases in such processes as denitrification and sulfate reduction. Consequently, the exchanges of gaseous carbon, nitrogen and sulfur between aquatic ecosystems and the atmosphere are changing. The Global Biology Research Program will conduct investigations focused on these changes and their consequences on C, N, S and P global cycles.

The issue of inputs to the oceans is central to global biogeochemical cycling. An important, unresolved case is the nitrogen cycle. A basic question is open: what controls the long-term nitrogen balance of the oceans?

It is very probable that the global marine nitrogen cycle is substantially affected by major glacial events. Certainly, the processes of soil denudation by advancing glaciers, the variability of terrestrial runoff, and the exposure and subsequent reflooding of major estuaries and coastal areas significantly alter the fluxes of nitrogen to and from the ocean, as well as the reservoir of nitrogen within the oceans. It may be that during periods of glaciation the oceans provide a sink for nitrogen, while during interglacials they act as a source. Thus it may also be true that a "balance" in the nitrogen cycle can only occur over periods of 10^5 years, and that glaciations play a crucial role in replenishing nitrogen in the oceans.

There is even uncertainty about carbon flux to the ocean. In fact, we do not know the total primary production of the world's oceans to within 50% accuracy. It is to this research issue that we turn next.

II.3.1 The Carbon Cycle and Ocean Primary Productivity.

Current estimates of marine primary production range from 20 to 55×10^9 tons of carbon per year, which accounts for 10 to 30 percent of the total annual global carbon fixation. Two factors of equal importance account for the large uncertainty in oceanic carbon fixation. First, the methodology used to estimate primary productivity (the ^{14}C method) may underestimate productivity per unit area by a factor between 3 and 10 in oligotrophic (gyre) regions. The large area of gyre activity magnifies this error. Second, the highly productive regions--high latitude oceans,

coastal and continental shelf regions, and upwelling regions-- exhibit a wide range of spatial and temporal variability which introduces substantial uncertainty for large scale estimates. This has hindered our understanding and our ability to estimate accurately global productivity and subsequent carbon and nitrogen fluxes.

II.3.1.1 Limitations of the Methodology.

DeVoys (1979) concluded that values for global primary productivity based upon the standard ^{14}C methods are at least 40 percent too low. Other investigators have found that the rates of incorporation of various organic compounds by bacteria in the euphotic zone exceed the rates of photosynthetic carbon fixation measured by conventional ^{14}C techniques (Andrews and Williams, 1971). Moreover, offshore studies indicate that a large fraction of photosynthate is consumed by microheterotrophs and respired as $^{14}\text{CO}_2$. Thus, it is not counted in total fixation (Geiskes et al., 1979). The ^{14}C uptake subsequently lost to grazing, cellular death independent of grazing, extracellular release of dissolved organic carbon, and respiration could account for as much as three times the photosynthetic rate measured in a 24 hour experiment. Furthermore, the experimental vessel may restrict nitrogen and phosphorus availability.

II.3.1.2 Undersampling in Regions of High Variability.

The uncertainty in current estimates of primary productivity in the major regions of the world's oceans are partly a result of undersampling the highly variable coastal and upwelling eutrophic zones. The processes that lead to upwelling and its associated high productivity include: geostrophy, the "upwelling" driven by the hydrodynamic balance of large scale ocean currents, wind driven turbulent mixing and upwelling due to the movement of surface waters offshore; the influence of bottom topography on

both mean currents and water motion driven by tidal forces; and the mixing associated with frontal regions, river and estuarine plumes, and the boundaries of eddies.

Several biological and physical oceanic processes must be sampled on different space and time scales to provide correct estimates of primary productivity, for the following reasons:

Wind-driven meso- and microscale processes are dominant factors in coastal eutrophic regions. These generally complex, episodic, nonlinear processes can act over a range of spatial scales from a few centimeters to hundreds of kilometers.

Similarly, oceanic fronts and eddies span a wide range of spatial and temporal scales.

The influence of bottom topography--on both periodic and a-periodic fluctuations of ocean currents, fronts, eddies, plumes, and island waters--has an equally wide spatial and temporal variance; and is also geographically diverse.

The extent of these various processes and the time scales over which they operate are poorly known, at present. Consequently, several biological and physical oceanic processes must be sampled on different space and time scales. Since phytoplankton abundance is a measure of primary productivity, synoptic measurements of phytoplankton that integrate temporal events with spacial distributions can elucidate the mechanisms of change in both biological and physical processes, as well as significantly reduce the errors in primary productivity estimates.

The large range of the time scale and widespread distribution for various processes mesh with several measurement platforms. Measurements made on a ship, or even a fleet of ships, cannot duplicate areal coverage provided by aircraft and satellites. In

many respects, these platforms collect mutually exclusive but complementary data sets, all of which are required to properly assess problems of abundance and distribution of phytoplankton.

By integrating recent advances in remote sensing with suitable sampling strategies, it is now possible to reduce significantly the variance in estimates of phytoplankton abundance and population growth rates and the associated fluxes of carbon in coastal and upwelling eutrophic regions.

**** Aircraft Remote Sensing.** Remote sensing by aircraft can fill a critical gap between conventional measurements made from ships and those within the current capability of satellite sensors.

Parameters that can be measured from aircraft platforms, such as salinity and chlorophyll fluorescence, are at least a decade ahead of those that can be measured from space. Airborne laser fluorosensors, in the "active" remote sensors class, fire laser pulses into the water column from low flying aircraft. The induced emission spectrum is sensed in several narrow spectral bands, allowing Chlorophyll a and other pigments, depth, and turbidity to be measured. The microwave radiometers, in the "passive" remote sensors class, measure the natural microwave emission of the water surface and provide remote measurement of water surface temperature and salinity within 0.5 degree C and 0.5 ppt accuracy (Kendall, 1981).

Two experiments have demonstrated the effective use of the interactive multiple platform sampling strategies that are required to investigate major coastal and upwelling processes. The Superflux Project, sponsored jointly by the National Aeronautics and Space Administration (NASA) and the National Marine Fisheries Service (NMFS) demonstrated the use of remote

sensing in studying the effects of estuarine outflows on shelf ecosystems. Three interactive aircraft-boat experiments conducted in 1980 studied the Chesapeake Bay plume and the adjacent continental shelf region. The parameters examined were salinity, light penetration depth (Raman scattering), chlorophyll fluorescence, and the relative abundance of golden-brown phytoplankton species (diatoms and dinoflagellates).

The Nantucket Shoals experiment, conducted in May 1981, used the same set of remote sensors as the Superflux Project to investigate the coupling of biological and physical processes in a topographically controlled upwelling system. The synopticity of the measurements of both physical and biological properties that can be provided by aircraft sensors, together with measurements of vertical properties, chemistry, and biological rates obtained from conventional techniques over the appropriate time scales, has permitted a thorough analysis of the dynamics of the Nantucket Shoals ecosystem.

**** Satellite Remote Sensing.** The Coastal Zone Color Scanner (CZCS) on the Nimbus-7 satellite was specifically designed to detect upwelling from variations in phytoplankton pigments. It has been demonstrated that changes in ocean color can provide a quantitative estimate of chlorophyll concentration (Gordon, et al, 1980; Smith and Baker, 1981) for oceanographic regions with an accuracy of 0.3 to 0.5 log C (where C is the chlorophyll concentration). Synoptic data from the Southern California Bight revealed significant temporal and spatial variation, and richness of detail. This information is impractical to obtain from shipboard data alone.

The chlorophyll images from the Nimbus-7 CZCS have been used to develop an algorithm to estimate primary production

(Smith, Eppley and Baker, 1981). However, prediction of primary productivity from CZCS chlorophyll data is limited by the high standard error associated with attempts to link biomass to growth rates. Yet, this work indicates that concurrent ship and satellite data, with an appropriate sampling strategy, can be utilized to provide a more accurate assessment of oceanic primary production on a regional basis. Equally important, an appropriate sampling effort applied to coastal zones and upwelling areas of the globe could significantly reduce the uncertainties of the estimated productivity of these areas.

II.3.2 Nitrogen Exchange between the Oceans and the Atmosphere.

The carbon content of the ocean is about 4×10^{19} g C, approximately 50 times higher than that of the atmosphere, or 13 times higher than the combined inventory of the atmosphere (7×10^{17} g C), land based biosphere (8×10^{17} g C) and humus (1.5×10^{18} g C). Assuming the relative accuracy of these numbers, one can argue that the atmosphere should be in approximate equilibrium with the ocean, able to adjust rapidly to changes in biological productivity that affect concentrations of CO_2 in surface water. Productivity is controlled mainly by the supply of nutrients, nitrogen and phosphorus, from below. A lower level of CO_2 could be explained if we could argue for a higher concentration of dissolved nutrients in the past, or for an enhanced supply of cold bottom water. In either event it is clear that we need to understand the physical, chemical and biological factors, that regulate the concentration of oceanic nutrients.

As discussed in the Introduction, the current view is that the ocean gains nitrogen by in situ fixation, by transfer from land in rivers, estuaries and marshes, and by delivery from the atmosphere. Nitrogen is lost from the system by denitrification

to either N_2 or N_2O , by nitrification releasing N_2O , and by incorporation in sediments. The sink terms are better known, and indicate contemporary loss of N at a rate of approximately 10^{14} g $N\ yr^{-1}$ --which implies a lifetime for oceanic nitrogen of about 10^4 years. The rate at which nitrogen is lost by nitrification and denitrification may be currently larger than the rate at which it is supplied by in situ fixation and transfer from terrestrial systems. In a broader context, there is the possibility that the oceanic nitrogen budget may not be in steady state on time scales of less than 10^4 to 10^5 years and there may be important associated variations in climate.

Broecker (1979) emphasizes the role of phosphates, and suggests that fluctuations in CO_2 might be attributed to the changes in oceanic productivity that are associated with the transfer of phosphorus from coastal sediments. There is insufficient evidence to support the view that phosphorus is a limiting nutrient.

II.3.3 Riverine Flux of Carbon, Nitrogen, and Phosphorous to the Coastal Oceans.

The magnitude of the riverine flux of carbon and nutrients to coastal oceans is an important component of the interactions of major biogeochemical cycles. The flux of nitrogen and phosphorus may substantially determine the amount of carbon fixed in primary productivity of the coastal oceans, and carbon fixation may constitute an important climate regulating mechanism in the global system. Consequently, a greater understanding of the magnitude and processes that bring these critical nutrients to coastal waters is an essential element of the Global Biology Research Program.

Rivers transport dissolved and particulate materials from the land to the oceans. Dynamic processes within the river system store and transform the materials being transported, such that

the quantity and chemical quality of the material exported is considerably modified from the parent material. Rivers function on several time scales. The first is on the order of 1-10 years, with variations induced by precipitation and routine storms. Episodic events, such as floods and hurricanes, occur on the scale of 10-100 years, and may result in discharges comparable to the sum of pre-event years.

Rivers are among the most poorly documented and understood components of the earth's biogeochemical system. The major research issues include:

- ** The total riverine flux to the marine environment of carbon, nitrogen and phosphorus is unknown. Human populations tend to aggregate near river and coastal environments, therefore the anthropogenic impacts on these regions must also be addressed.
- ** The terrestrial inputs to the river system, the mobilization mechanisms along a redox sequence and the associated evolution of biogenic gases are poorly understood.
- ** The disposition and fate of the riverborne carbon, nitrogen, and phosphorus in the marine environment is a function of the chemical condition of these materials (e.g., how refractory or labile), the response of plankton, and the sediment transfer processes. These rates are unknown.

Further, rivers are an integral feature of human populations. They support major agriculture and inland and coastal features; and they provide water. Rivers are highly sensitive to changes in land use patterns, impoundments, nutrient input and channelization. Given projected demands for hydroelectric power

and land-use requirements, the sensitivity of rivers is enhanced. These human-induced events have considerable impact on the role of rivers in geochemical cycles.

II.4 Modelling: A Methodology for Global Biology.

A science that chooses the Earth as its fundamental biogeophysical unit faces extraordinary scientific difficulties. The questions that can be asked (and conceivably answered) about ecosystem dynamics at this level are not immediately obvious; nor is it clear how to formulate theories or experiments for a system of this size. From an astronomical viewpoint, the scale is not particularly grand; geophysics, meteorology and astrophysics often measure systems of at least planetary magnitude. Yet, the concept of biological systems that work on a planetary scale is new; and initially it might seem as if the paradigms for understanding ecosystem dynamics at this level are lacking. However, the application of traditional ecological concepts provides a starting point.

A classical concept in ecology is a model of the flow of either material or energy. The model may be static or dynamic. Time scales and levels of complexity may vary widely, and perturbation may be included or excluded. Using models, it is possible to explore questions about ecosystem stability, resilience, and other system-level characteristics. An objective in this research area is the development of mathematical models which accurately represent the dynamics of the global cycles of carbon, nitrogen, phosphorus and sulfur.

Additional models should be developed to chart the planetary energy budget, the water cycle, and the oxygen cycle. These models will eventually need to be integrated with the models of the major biogeochemical cycles; further, it will be necessary to undertake the development of process oriented models to

develop a better understanding of elemental interactions.

Initially, the modelling component of the research program will be focused upon the major biogeochemical cycles and some of the key processes that underlie the linkages in these cycles. Scientifically rigorous global biogeochemical models will be among the first tools needed to address questions dealing with past, present and future states of these cycles. Four elements--carbon, nitrogen, phosphorus and sulfur--are of special interest in the study of global cycling. As with all elements, each of these four follows a path through the biosphere that is determined partly by its biogeochemical properties. As discussed in chapter I, human activity has significantly perturbed these cycles (Table II.4.1) and, as a consequence, certain indicators of the state of particular cycles (for example, the level of atmospheric CO_2) have moved well outside their recent historical distributions.

Some of these changes are well documented on the global scale. For example, we now have reasonably good estimates of the changes in global stocks of carbon in terrestrial ecosystems over the past century as humans convert some forests to agriculture and harvest others for fuelwood (Houghton et al, 1982; Moore et al., 1981). The consequences of these changes, however, for the cycles of N, P and S have not been evaluated. Several efforts to synthesize the global cycles of C, N, S and P have been made in several conferences held by the Scientific Committee on Problems of the Environment (SCOPE Reports 7, 13, 16, 17), and recently SCOPE has sponsored an Elemental Interactions Conference (Sweden, June 1981).

Thus far the most advanced work in modelling biogeochemical cycles has dealt with the carbon cycle. There is already an extensive history (Bolin, 1977; SCOPE-16, Bolin et al., 1981; and Moore, 1982). Global carbon cycle models developed thus far have tended to be globally aggregated, with a comparatively small

number of global-scale well-mixed reservoirs (e.g., Bascastow and Keeling, 1973; Oeschger et al., 1975; Bjorkstrom, 1979). Although somewhat abstract, these models provide considerable insight into the dynamics of the carbon cycle and are used for projecting atmospheric CO_2 concentrations. Until recently, these models have employed relatively simple causalities with nonlinearity entering only to treat the carbonate system in the oceans and possible CO_2 stimulation of terrestrial vegetation. Elemental interaction has not been considered. However, even these models have been oversimplified by using a comparatively small number of global-scale well-mixed reservoirs. It is clear, that results obtained with such a crude representation of the global system (using only a few reservoirs--boxes--in exchange with each other) described by first order processes are to be considered only as zero order estimates of natural processes. Further, it is difficult to consistently parameterize such models because the variables in the model correspond in reality to such large time and space averages that they are difficult to define precisely even with good data. The inadequacy of such results has been obvious, for example, in the attempt to use such simple models to obtain answers to questions regarding the role of the oceans or terrestrial biota in the global carbon cycle. On the other hand, immediate development of two dimensional or even general circulation models for the ocean, or for complex processes models for terrestrial biota, is likewise inappropriate. Even if we must ultimately resort to such complex models of the ocean circulation or of process level attributes to deal with the transfer of matter, there are many particular problems that may be studied with simple models. More important will be the development of conceptually clear models of the global cycles that include an initial state, alterations by humans, and the effects of elemental interactions on the cycles. Any more elaborate studies should be preceded by the development of a hierarchical suite of models of increasing sophistication to formulate properly the complex experiments.

Thus the objective should be the development of a collection of large-scale global biogeochemical models, that are consistent with both process-level studies (McGill et al., 1981) and broader biome scale models (Broecker et al., 1979). Such models would be used to test the sensitivity of our understanding of the biosphere against various assumptions and theories of how the biosphere functions on both large and small scales.

III. RESEARCH TASKS

In this chapter the principle research tasks are described, and associated with the research issues discussed in the previous chapter. The research tasks are restricted to a ten-year time frame. However, emphasis is given to tasks that need to be initiated during the first five years. The research tasks focus on the following objectives:

1. To establish a basis for assessing the major pathways and rates of exchange for carbon, nitrogen, sulfur and phosphorus into and out of terrestrial ecosystems that have been disturbed by humans.
2. To establish a basis for extrapolating biospheric effects from local rates of anaerobic activities, paying particular attention to the role of reduced gases and their key oxidation products.
3. To establish a basis for assessing the major pathways and rates of exchange for carbon, nitrogen, sulfur, and phosphorus, into and out of the world's oceans.
4. To develop mathematical models that represent accurately the dynamics of the global cycles of carbon, nitrogen, phosphorus and sulfur, including their interactions. To develop process-level mathematical models for examining key processes that control the dynamics of elemental interactions.

It is important to note that each of these tasks has linkage with other NASA programs, as well as with other agencies' programs, and that coordinating these efforts is integral to accomplishing this research objective. (See Management Operating Plan, Sect. IV).

III.1 To establish a basis for assessing the major pathways and rates of exchange of carbon, nitrogen, sulfur, and phosphorus to and from terrestrial ecosystems.

As previously discussed, there are three tasks that must be addressed to accomplish this research objective. They are:

1. To develop better estimates of the rates of anthropogenic disturbances.
2. To develop accurate transfer functions relating the type of perturbations and ecosystem characteristics to changes in carbon, nitrogen, sulfur and phosphorous cycles.
3. To understand the controls of the pathways and interactions involved in carbon, nitrogen, sulfur, and phosphorus gains and losses in terrestrial ecosystems.

III.1.1 Measuring the rates of human disturbances in the vegetation and soils of the Earth by remote sensing.

This task requires direct measurement by remote sensing of the rates of natural and anthropogenic alterations in terrestrial ecosystems. Four subtasks must be completed in sequence to accomplish this task:

1. The existing data on land cover and land use must be evaluated and standardized into a usable format.
2. The land area of the earth must be divided into ecologically meaningful regions suitable for study by remote sensing.
3. A stratified sampling plan must be developed.
4. Representative areas must be selected and ground-based programs must be initiated within each of the regions defined above.

The first subtask addresses the issue of the adequacy of currently existing processed data; the latter three constitute the basis for a remote sensing strategy for the land use data base.

III.1.1.1 Existing Data.

Before initiating a program of new data acquisition, a critical review of the present status of existing data on the current state of the planet's vegetative cover and soil condition is necessary. This will allow an evaluation of available data and will identify critical data gaps. Therefore, the data acquisition program will take its lead from an initial review of the available data.

The review should focus on land use change and its effects upon the vegetation and soils. Agricultural land area data, collected by the national governments and international organizations and agencies, represent the primary sources of synoptic data on land use and land clearing rates. These data

include the FAO Production Yearbooks, the International Institute of Agriculture, and independent reviews (Revelle and Munk, 1977; Meyers, 1980; Houghton et al., 1982). The disparity between the FAO data and the Meyers (1980) data is striking. Controversy centers on rates of tropical deforestation. The difficulties of biome-wide assessment reported in many studies are, in part, due to the nature of the method of data acquisition by FAO. FAO relies heavily on obtaining primary data from national governments being surveyed. In many tropical countries, cutting and clearing data may be no more than informal estimates. For example, Meyers (1980) points out that some countries will disseminate outdated figures. Indonesia continues to report that its forest cover is estimated at 1,200,000 km²--a figure that is actually 20 years old. The widespread logging, clearing for agriculture, and intensified shifting agriculture of the last 30 years, is not represented. Meyers (1980) suggests a figure of 800,000 km². Persson (1977) emphasizes that, in Zaire, the accuracy of data is probably no more than plus or minus 40%. Thus, any use of existing data must be made with a degree of caution.

The extent to which experts agree on the essence of deforestation in the tropics is discouraging. Richardson (1970) suggests that, "There is no technical reason why tropical hardwoods should not substitute extensively for softwoods in the British markets. There is certainly no shortage of them. Using FAO Global Statistics and National Returns, it has been demonstrated that at a projected 1985 rate World Imports (80 million M³ annually), there are sufficient tropical forest resources to last for 400 years." By contrast, the World Bank's Forestry Sector Policy Paper (1978) concluded: "The existing forest stock in developing countries (estimated at 1,200 million ha of mature forest) is currently being removed at a rate of 15 to 20 million ha per year. At this rate, assuming no growth in demand, the remaining tropical forests will disappear in about 60-80 years." Richards (1973) went further in his pessimism:

"The tropical forest ecosystem as we have known it will virtually disappear from the face of the Earth by the end of the 20th century." But as Spears (1979) notes, "One of the problems we face in trying to analyze the future fate of the tropical forest is that soil scientists, land use planners, botanists, agronomists, meteorologists, sociologists, hydrologists, ecologists and environmentalists all tend to look at this issue from a parochial viewpoint. The volume of specialized literature which has grown up around the subject would fill St. Paul's Cathedral, whereas the number of papers which tackle the subject in an 'holistic' way would probably fit into my briefcase."

However, a valuable new data set is slowly being formed. Within the past five years, a number of countries have published their own comprehensive and accurate surveys, mostly by using remotely sensed imagery. The results have been important: in the Philippines, these new estimates show only 38% forest cover in contrast to former estimates of 57%; Thailand now possesses 25%, compared with the 48% figure of earlier reports (Meyers, 1980a); forests in the Ivory Coast have diminished by more than one-third in eight years (Persson, 1977), and Costa Rica has lost one-third of its forest cover in ten years (Cannon et al., 1978). Apparently, many countries--such as Brazil and Indonesia-- have also instituted comprehensive remote sensing programs. These data are not generally available to outside investigators, and they have not been critically summarized. As a final note, there will be available soon new estimates by FAO for land use patterns that are based on remote sensing data that may be a considerable improvement on previous data sets (Singh, personal communication).

A critical review by NASA will provide the basis and structure for future data acquisition and will allow the development of an information retrieval system before new data acquisition begins. Further, modelling groups can begin working with consistent sets of existing data, then later incorporate

improved data sets. New data on land use will be developed on remote sensed imagery and ground truth. There are three major components or subtasks associated with this effort that will be discussed individually.

III.1.1.2 Regionalization.

The land area of the earth must be divided into ecologically meaningful regions suitable for study by remote sensing. A number of approaches to this task have been suggested. Some groups have used grids of latitude and longitude (Lieth, personal communication). Others have defined a series of biomes (e.g., tropical forest, alpine tundra, natural grassland) and determined the areal extent of each biome in a range of geographical areas (Moore et al., 1981). Approaches based on either biomes or Holdridge (1967) Life Zones seem most promising. For example, upper montane tropical forests function very differently from lowland rain forests in the same geographical grid. Further, the difference in scale among geographic regions, and the wide variation in rates of land use change among regions of the same ecological type, requires the classification system to reflect the geographical potential for disturbance.

Initial attempts at classification might employ a simple physiognomic breakdown, such as that used by UNESCO. This system includes such categories as closed forests, open forests, scrub and shrubland, dwarf scrub, and herbaceous vegetation, and permits further refinement where the vegetation is better known. The proposed classification system will distinguish the extremes of aboveground biomass within most regions. Discrete categories of vegetative cover do not exist naturally; rather, continual changes in carbon and nutrient storage and cycling, and of species composition, can be distinguished along environmental gradients. However, aggregation of sites with generally similar climates can provide a useable system. Such a classification

scheme assumes that sites within the same class will respond to disturbance more similarly than sites in the same geographical coordinates. In addition, this system might be complimented by overlapping a Holdrige Life Zone system. This system is based on the correlation of temperature and water, and can work with 0.5 degree x 0.5 degree mapping grids. However, an expanded 5 degree x 5 degree grid system may be, initially, more appropriate.

Accurate vegetation maps are basic to any appraisal of ecological type. Vegetation maps take two general approaches. First, potential natural vegetation maps describe the natural vegetation of a region prior to disturbance and after succession has run its course. The second approach defines the actual vegetation, including agricultural crops, virgin forests, successional stands, and other communities. Maps of actual vegetation distinguish discrete stages in succession and can be used to estimate the current standing stocks of carbon and nutrients.

The usefulness of potential vegetation maps is limited by the high probability that repeatedly disturbed sites lose some of their potential to regenerate vegetation to the same level of total and species diversity, biomass, and nutrient content, that was the pre-disturbance norm. As our understanding of ecosystem response to disturbance expands, potential vegetation maps and transfer functions which describe disturbance will be altered accordingly. In addition, different ecological types will respond to repeated disturbance differently. This problem is addressed in the development of transfer functions, Section II.1.2.

III.1.1.3 Stratified Sampling Plan.

A stratified sampling plan should be developed to determine changing land use patterns and the associated changes in vegetation. However, a wall-to-wall census, at the same level of resolution over the entire surface of the planet, is both impractical and unnecessary.

The total area of land that supports vegetation is approximately $147 \times 10^6 \text{ km}^2$. Since each LANDSAT scene covers about $21,900 \text{ km}^2$, without overlap, worldwide coverage of land would require about 6700 frames. However, 12,000 frames would allow coastal waters and freshwater lakes to be incorporated. Cloud cover, equipment failures, difficulties in reception and interrupted operation of satellites would likely double the total number of frames needed to 24,000. If changes in the vegetation are to be detected, the total would probably be doubled again to approximately 50,000 frames, a number that is impractical, at least initially.

Additional limitations intrinsic to the satellite system make a sampling program more appropriate than a complete inventory program. For instance, receiving stations cover less than 50% of the earth's surface at present and tape recording of data over areas not covered by receiving stations is limited. The satellites do not operate continuously, and cloud cover limits the usefulness of many images. Finally, imagery must be obtained from certain types of vegetation at particular seasons. Therefore, special attention is required to assure that imagery represents the appropriate time frame. To obtain appropriate imagery for the entire earth over any period of less than several years is not feasible. There is no alternative to the use of a stratified sampling system, despite advances in automation, interpretation of imagery, and handling of data. Consequently, the criteria for stratification should be 1) the magnitude of the

carbon and nutrient reservoirs available for change, 2) the probability of change, 3) the size of the change, and 4) the time during which change will remain detectable.

The stratification may be based on existing maps of vegetation, on demographic, or on other ancillary data that indicate areas with the greatest probability of change in carbon and nutrient storage. If it is possible to isolate the majority of change (> 90%) in a small area (< 5% of total area), then the accuracy can be enhanced appreciably without a large increase in effort. The measurement of changes in the vegetation and soils will require data that span at least a year. Accuracy will increase as period increases and the extent of the changes measured becomes greater.

III.1.1.4 Representative Areas.

The objective is to select areas that are representative of the rate of land use change and small enough to minimize the data generated in sampling. Moreover, some fraction of the representative areas (ideally, some portion of each representative area) should be accessible for ground-truth or over-flight by aircraft investigations to confirm and detail the remotely-sensed patterns.

Priority should be given to projects which measure the consequences of land use changes in four areas: large-scale temperate agriculture, boreal and tropical forests, savannahs, and wetlands. Large-scale temperate agriculture is described in a large data base from agricultural experiment stations, the large changes in C, N, S, and P associated with continued cultivation (Van Veen and Paul, 1981; Voroney et al., 1981), and intensive efforts to understand temperate-zone agriculture in an ecosystem context. The work currently underway at Colorado State

University (C.V.Cole, personal communication) is a notable example. In contrast, tropical and boreal forests are described poorly in available ground-based and remote sensing data. In addition, the rates of disturbance in tropical forests are large (Lanly and Clement, 1979; Tosi, 1980), but the precise rate of land clearing in different regions is very poorly known.

Excellent work on tropical forests is underway in many areas, including the Ivory Coast (Bernhard-Reversat, 1977), Venezuela (Herrera and Jordan, 1981), and Costa Rica (C.Jordon, personal communication). For this study, the La Selva site in Costa Rica offers the advantages of a long-term research site with substantial reserved land in a region that is developing rapidly. The assurance of its continued existence makes it an appropriate site for developing techniques to evaluate long-term tropical forest land use change by remote sensing.

Savanna ecosystems are characterized by a mixture of grass and woody vegetation. They occur predominantly in the tropics, occupying those regions between the arid deserts and the moist woodlands. Their significance in regard to the biogeochemical cycles is two-fold:

- ** They exhibit marked natural fluctuations in productivity--up to 500% between seasons, much greater fluctuations than those exhibited in the arid regions.
- ** They are currently being subjected to great changes by humans.

In contrast, the main crop-growing areas of the world and most of the northern hemisphere have already been changed and are now relatively stable--whereas the savannnas are subjected to rapidly expanding human activities.

The major determinants of savannas are rainfall, soil type, large herbivores and fire. These determinants result in a gradation from moist or mesic dystrophic woodland savannas with few large herbivores, to semi-arid open savannas high in nutrients and with many large herbivores. Fire increases in frequency and significance with increasing rainfall, but decreases as the vegetation becomes closed woodland.

The relative amounts of woody and grass vegetation factor into the biogeochemical cycles because they differ with respect to (1) carbon and nutrient storage; (2) times and rates of production; and (3) turnover rates of litter (<1 year for grass, several years for woody vegetation). The ratio of woody vegetation to grass in the savanna regions is changing in different ways in different places. These changes are a result of bush encroachment, agricultural clearing, the use of fire to increase grazing lands, and the depletion of woody vegetation for firewood.

The final priority area suggested is wetlands. Wetlands are chosen because: they are the major natural terrestrial source of many reduced trace gases in the troposphere; they represent the land/sea interface; and they are being changed at a rapid rate, primarily by being drained and converted to agricultural and other uses. The area and status of wetlands in the U.S. has been carefully surveyed. Good results on wetland species and biomass determination with Landsat MSS and Thematic Mapper bands are already being obtained by several investigators (Bartlett and Klemas, 1981).

Consequently, methods to assess the impact of drainage on trace fluxes could best be developed as part of the wetlands study. The transfer functions developed as part of this study could then be extended to other areas of wetland conversion measured by remote sensing. Sampling of the representative areas to detect rates of

disturbance and land use change should be carried out continuously.

The frequency at which the results are evaluated could vary, but five years should be the minimum interval. Regions of rapid change or life zones critical to the global cycles of C, N, S, or P, would require more frequent sampling. Comparisons among similar representative regions should be made occasionally to confirm that the representative areas remain so.

In addition, the selection and repeated sampling of representative areas will provide the means to evaluate catastrophic or unusual events in any class. Each class will have at least one well-sampled representative area, so that--even if no catastrophic events occur in sampled areas--there will be a well-examined, similar control area for comparison against the perturbed areas. The importance of experience with the specific types of vegetation in question cannot be over-emphasized. The complexities of succession, partial harvest, grazing and other types of disturbance are familiar to local students of the vegetation. Though global in scope, these and other factors emphasize the importance of a regional approach to the remote sensing of vegetation. The approach would place major reliance on regional experts and centers of scholarship.

Finally, ground-based science at representative areas will help determine the transfer functions that are associated with particular systems and particular disturbances. It is to this determination that we now turn.

III.1.1.5.Summary

In summary, the following strategy will be used for providing data to global ecosystem models:

1. Subdivide the land and oceans into meaningful and manageable regions. A combination of the regions defined by Moore, et al,(1982) and a variant of the Holdridge Life Zones could provide the needed sensitivity.
2. Establish a global data base, in a format suitable for model input.
3. Within each region select and survey pilot test sites for updated or more detailed inventories (by remote sensing where necessary) and store data in the data bank. Sites are selected as follows:
 - a) sites representative of the entire region (using random sampling approach)
 - b) sites where rapid change is occurring (e.g., deforestation) or sites which are exceptionally productive (e.g., upwelling regions).
4. Where necessary, perform field studies to obtain conversion factors for relating other ecological properties (e.g., gas emission rates or biomass) to those which can be mapped remotely (e.g., vegetative land cover, etc.)
5. Extrapolate pilot test site data to the entire region and relate remotely sensed data to other model parameters.
6. Evaluate advanced remote sensors being developed for quantitative surveys of global ecosystem properties.
7. Define requirements for new remote sensors and data analysis techniques which need to be developed for global ecosystem monitoring in:
 - a) survey mode - data calibrating and exercising models, and updating data base
 - b) alarm mode - near-real-time data to alert investigators to abnormally rapid degradation of the environment in some critical area of the world.

III.1.2 Developing Transfer Functions

In addition to changes in the area of classes of vegetation, the program must consider successional change. Succession is especially important in forests because of their large carbon and nutrient content. The ability to recognize successional communities will hinge on their spectral characteristics, the precision with which they can be recognized on the ground, and knowledge of the patterns and areas of succession for major vegetations.

The most difficult problem will be to measure changes in soil carbon. Certainly, the direct classification of soils through satellite imagery will not be possible, as it has been for many vegetation types, because plant canopies generally hide the soil from view. However, the organic content of soils might be predicted from the vegetation because the two are so closely coupled. The intimacy of this relationship is great enough to encourage use of remote sensing techniques in interpreting changes in soils following disturbances of the vegetation. The task here is to develop accurate transfer functions relating the contents of ecosystems to the time since a particular class of disturbance. Different transfer functions are needed for each functional unit (or life zone) studied, since the transients occur at very different rates in different life zones. For example, it takes 60-80 years of agricultural land use to lose half the organic carbon in a Canadian prairie soil, but only 2-3 years in an African rainforest (Nye and Greenland, 1964).

There are two basic, though overlapping, approaches to developing transfer functions: (1) ground-based fundamental ecology and (2) the use of remote sensors to estimate and then compare carbon and nutrient stocks in a variety of ecosystems at different stages of succession. The latter course will be pursued more rigorously while remaining cognizant of the former.

The ground-truth investigations at representative areas will serve to integrate basic ecology with remote sensing methodologies.

III.1.3 Understanding the controls of the pathways and interactions involved in gains or losses in terrestrial ecosystems.

Work on this task runs a clear danger of including all of environmental microbiology and ecosystem-level ecology. The process studies themselves are probably most efficiently done outside of NASA, although The Program may sponsor workshops, at appropriate times, designed to integrate information from diverse sources. Aspects that are not currently being addressed by other agencies are: the development and testing of conceptual models designed to examine the linkages among elemental cycles and among major ecosystems (terrestrial, coastal marine, open ocean), and the examination of the long term nature of the cycles. In that sense, the discussion sections in II.4 and III.4 on modelling are particularly relevant to exploring elemental interactions.

III.2 To establish a basis for extrapolating from local rates of anaerobic activities to biospheric effects and in particular explore the role of reduced gases and their key oxidation products.

III.2.1 Quantifying anaerobic processes.

Past microbiological research has focused on the response of individual organisms to environmental conditions. Recent work demonstrates that the complex interactions of species in a microbial microcolony produces a community response to environmental conditions which is substantially different than that of single species. Consequently, further research must be

designed to clarify the community response to an array of environmental conditions.

The development of new methods that do not isolate microbes from their functional unit--the microcolony or the microhabitat--are required to study the processes and rates by which reduced gases are generated. Further, the relationships between activity and the biomass, and/or establishment of redox gradients by inhibition or competition, need to be clarified by studies of the whole microbial assembly.

The ability of an ecosystem to generate reduced gases by anaerobic microbial activity is controlled primarily by the physical and chemical environment of the microbial microclimate. A substantial body of data supports the contention that the number of microorganisms does not limit the chemical transformations mediated by them. In addition, reduced gases must pass through oxidation traps of bacteria which can oxidize the gases (e.g., H_2S or CH_4). The mechanisms by which reduced gases can pass through these traps need to be defined and their activity quantified. Bubble formation, tidal pumping in estuaries or biological conduits such as higher plants may be important to these processes. The effect of microbial mechanisms on the gross flux of reduced gases to the atmosphere must be quantified for different vegetative communities and varying environmental conditions. Consequently, response curves describing reduced gas flux must be developed for anaerobic microbial complexes specific to different ecosystems under an array of environmental conditions.

The response curves must be applied to vegetation maps and environmental conditions to develop gross estimates of the potential generation of reduced gases. Changes in land use patterns and the transformation of plant communities will potentially effect the gross generation of reduced gases on a global scale. Therefore, the integration of land use data and

response curves for anaerobic generation of reduced gases will demonstrate important biological feedbacks from the biotic and abiotic elements in the biosphere.

III.2.2 Estimating the global cycle of specific trace gases

As discussed in Section II.2, the trace gas densities in the atmosphere are changing. Current evidence suggests that atmospheric concentrations of CO, CH₄, N₂O, and certain halocarbons have been increasing during the past few decades. These changes in atmospheric chemistry are linked to biological processes by a variety of hypotheses and theoretical models. Understanding the complex linkages among the biosphere, atmosphere, and climate, is one of the major scientific challenges of this decade. The following merely serve as examples of research tasks. They are not intended to represent research priorities.

III.2.2.1 Carbon Monoxide.

The primary research needs are designed to elucidate the role of the biosphere and human impacts on the global carbon monoxide cycle. They include:

- ** Intensive study of direct and indirect (through nonmethane hydrocarbon) production of carbon monoxide by vegetative sources under both field and laboratory conditions. Emphasis should be placed on quantification of baseline carbon monoxide flux from major vegetation types under a range of environmental conditions. The ecosystems that should be considered first are forests, both temperate and tropical, and the arctic tundra.
- ** Quantification of biomass burning as a source of carbon monoxide.

III.2.2.2 Methane.

The task is to quantify the global methane cycle. Global sources of methane are presently speculative; flux estimates for microbial fermentation in wetlands are based on a few limited measurements. The types of coastal and freshwater wetland systems thought to be major sources of CH_4 are being heavily impacted. The large-scale destruction of anaerobic habitats suggests that these areas may be an important source of methane flux to the atmosphere. Consequently, the priority measurements are the quantification of terrestrial biogenic and oceanic sources of methane, and the development of sampling and measurement approaches that will provide critical data:

- ** An enhanced program of ground-based methane flux measurements, with careful corollary measurements of other biogeochemical variables (e.g., soil water content, organic content, temperature, etc.), should be conducted in potential source areas such as wet tropical forests, swamps, salt marshes, and tundra ecosystems. Selection of experimental sites should take into account ongoing ecological research, primarily sponsored by the National Science Foundation Program, where data on nonmethane carbon fluxes and other environmental variables are available for potential source areas. Careful attention should be paid to both temporal and spatial variations in methane flux within any particular ecosystem.
- ** Because many of the natural areas for potential emission of methane to the boundary layer are remote, precluding ground-based flux measurements, a low-altitude flux measurement program should be attempted. Meteorological measurement techniques, described by Lenschow et al. (1981), might be combined with the NASA gas-filter-correlation infrared methane detection system (Sebacher and Harriss, 1982) to determine large areas of methane flux in the boundary layer. A necessary first step in preparing for aircraft flux measurement of methane would be to test the maximum response time, precision, and accuracy possible with the gas-filter-correlation system. Preliminary test flights for methane flux should be conducted over a natural gas field or other strong source.

** Factors that influence the solubility of methane in seawater and the exchange rate of methane across the air-sea interface need to be determined. Currently, the popular hypothesis that the ocean is neither a source nor sink in the global methane cycle rests on very limited data. A set of coordinated laboratory and field measurements is needed to examine the effects of dissolved organic materials, pH, microbubbles, and methane-oxidizing bacteria on water column concentrations of methane. Quantification of the influence of surface films and ocean surface roughness on methane exchange rates across the air-sea interface is also an important research need (see Broecker et al., 1980, for similar problems related to CO₂ exchange).

III.3 To establish a basis for assessing the major pathways and rates of exchange of carbon, nitrogen, sulfur, and phosphorus to and from the world's oceans.

This objective will be approached by focusing initially upon carbon and nitrogen through four specific research tasks. They are:

1. To quantify the rate of primary production in the world's oceans.
2. To quantify the flux of N from the atmosphere to the ocean.
3. To quantify the flux of N from the ocean to the atmosphere.
4. To quantify the riverine flux of C, N, S, and P to coastal oceans.

It is important to reiterate that each of these tasks has linkage with other NASA and National Science Foundation programs, and that coordinating these efforts is integral to accomplishing this research objective. (see Management Operating Plan, Sect. IV)

III.3.1 Improving Estimates of Primary Productivity in the Oceans.

The primary research task in this area is to improve annual global estimates of carbon fixation in the oceans by an order of magnitude. Our ability to estimate accurately phytoplankton production and the subsequent carbon and nitrogen fluxes in eutrophic coastal and upwelling areas is hindered primarily by the dynamic variability of the processes affecting production in these ocean regions. This is in marked contrast to our uncertainty of primary production in open ocean areas. Open ocean productivity tends to be relatively uniform; uncertainties in this area seem to stem from the technical problems associated with measuring productivity in low phytoplankton biomass waters. Recent developments in remote-sensing techniques and multi-platform sampling strategies now permit synoptic oceanographic data to be obtained, which was not previously possible. Consequently, it is practical to consider sampling strategies which would allow global determination of phytoplankton abundance, population growth rates, and subsequent related fluxes to be made with greater accuracy and with quantitative standard error of estimates. This research task has two primary components.

1. The ^{14}C methodology must be reevaluated.
2. Global estimates of primary productivity in areas of gyre activity and coastal shelf and upwelling areas must be improved.

III.3.1.1 Reevaluation of ^{14}C methodology.

Recent evidence suggests that the ^{14}C methodology may be responsible for errors of gross primary productivity estimates of the oceans by a factor of three in oligotrophic regions. The large area of gyre activity magnifies this error. This has lead to a potential error of 40% for global estimates (DeVooy, 1979). Heterotrophic activity and nutrient limitations within the experimental vessel may be responsible for these errors. Improved estimates of global oceanic primary productivity cannot be achieved without a reevaluation. For several reasons, the problem of accurately determining the primary productivity or growth rate of marine phytoplankton may be worse in the open ocean than it is in the other ocean provinces. It can be argued that phytoplankton in the open ocean are sensitive to stresses related to capture and prolonged enclosure. Further, they are more likely to be nutrient limited. When contained in the experimental vessel, they may be cut off from important sources of nutrients, such as nitrogen and phosphorus. The same problems apply to recycling by microheterotrophs.

In coastal and shelf areas, only 50% of the carbon fixed is recycled in the euphotic zone, compared with 90% or more in the deep ocean (Harrison, 1980). Problems with both the ^{14}C methodology and the underestimation of the deep chlorophyll maximum are responsible for substantial underestimates of oceanic primary productivity. If the total marine productivity is at least $45 \times 10^{15} \text{ g C yr}^{-1}$ and if this value is compared with the atmospheric input of CO_2 from fossil fuel combustion (estimated by Keeling (1973), $5 \times 10^{15} \text{ g C yr}^{-1}$), it is apparent that the removal of CO_2 by the photosynthetic activity of oceanic phytoplankton is a an important flux. A research effort will be initiated to reevaluate the ^{14}C method for estimating gross primary productivity. Grazing by heterotrophs and nutrient limitations imposed by the experimental vessel must be evaluated

for different phytoplankton communities. This effort should be aimed at developing accurate conversion rates for the data gathered with the ^{14}C method during the past 30 years of oceanographic research. This entails a program directed at developing methods to calibrate and convert past data to a usable form. Although important, such an effort will require a great many resources compared with remote sensing technology development. It is hoped that this entire effort will be closely associated with National Science Foundation activities.

III.3.1.2 Undersampling.

Most of the uncertainty in current estimates for primary productivity in coastal and upwelling areas results from undersampling regions that are highly variable in time and space. Hence, each fundamental process that determines material flux and the rates and extent of productivity, must be evaluated to provide an improved estimate of global productivity. The basic research tasks involved in the remote sensing or sampling aspect of determining oceanic primary production are:

- ** To determine the areal extent of upwelling and other high productivity processes and the time scales over which they operate.
- ** To measure distributions of properties associated with primary production over the major coastal areas of the world.
- ** To develop remote sensing techniques to assess primary production in the oceans.

Elaborating upon these tasks, we note that recent advances in remote sensing technology need to be integrated into a suitable sampling strategy for improving present estimates of global oceanic primary productivity. In addition, multiplatform sampling strategies must be developed to effectively examine the various processes that determine rates of primary productivity and

are responsible for the high degree of variability in coastal shelf and upwelling areas.

Remote sensing by aircraft should be used to fill the critical data gap between conventional measurements made from ships and satellite sensors. Salinity and chlorophyll fluorescence can be measured by airborne laser and microwave sensors. The Superflux and Nantucket Shoals experiments should serve as models for further development of multiplatform sampling strategies.

The CZCS radiance data (Coastal Zone Color Scanner) from the Nimbus-7 should be used to provide a synoptic view of the spatial and temporal variability in complex coastal regions and upwelling zones. An important research objective of the Global Biology Research Program will be to improve methods used to interpret remotely sensed data from the CZCS for the purpose of estimating primary productivity.

Concurrent ship and satellite data, with an appropriate sampling strategy, should be utilized to provide a more accurate assessment of oceanic primary production on a regional basis. Quantitative assessment of the spatial and temporal variability (patchiness) of chlorophyll over the large regions of the ocean should be conducted. This will require that a more complete understanding of the processes responsible for the variability in upwelling and coastal regions be integrated with rates of productivity derived from multiplatform sampling and remotely sensed data.

III.3.2 Determining the nitrogen flux from the atmosphere to the oceans.

This research task has two primary components:

1. To determine the nitrogen content in maritime rain.
2. To determine the rate of nitrogen fixation by marine organisms.

III.3.2.1 Deposition.

A field measurement program to quantify heterogeneous removal of nitrogen from the atmosphere to the oceans would require a careful study of NH_4^+ , NO_3^- , and organic-N in maritime rain. To understand removal processes, one would require data on the nitrogen content of marine aerosols as a function of particle size, nitrogen species in cloud water, and nitrogen species in sequentially sampled rain from a variety of (meteorological) types of precipitation systems.

The NASA Tropospheric Air Quality Research Program will soon initiate an increased research effort focused on homogeneous gas phase nitrogen chemistry in the troposphere. Field determination of heterogeneous removal might best be accomplished through coordination of research activities with the Tropospheric Air Quality Research Program.

III.3.2.2 Fixation.

By definition, nitrogen fixation is a biological phenonoma and properly a concern of the Global Biology Research Program. Only two genera of photosynthetic cyanobacteria capable of N fixation, Trichodesmium (Oscillatoria) and Richellia, have been found in the open ocean (DeVoys, 1979). These bacteria seem to account for all, or almost all, open ocean nitrogen fixation. The former is widespread, and is typically found in densities of <10 colonies per M^3 (one colony consists of approximately 30,000 cells), and it appears to carry out most of the fixation. The latter is only rarely observed, and exists within the frustule of large centric diatoms. For the present it will be ignored.

Bacteria capable of fixing N_2 have been isolated from

Trichodesmium colonies, but it appears that in colonial form, Trichodesmium fixes N_2 at rates sufficient to meet its entire N requirement for growth. A better understanding of the physiology of this organism, and its interaction with bacteria and other organisms commonly associated with its colonies, will come only after it has been cultured in the laboratory. Support for this research should come primarily from the National Science Foundation.

Since there is no reliable global estimate of the abundance of N_2 fixing cyanobacteria, even expanded knowledge of the physiology will not, of itself, elucidate the flux of N_2 from the atmosphere to the ocean. Air-borne lidar techniques that can sense the phycobilin pigments of cyanobacteria should be used to locate areas of high cyanobacterial density. In order for this sensor to be of use in quantifying Trichodesmium abundance, shipboard observations would be necessary. Trichodesmium can regulate its depth in the water column, and lidar sensing cannot distinguish between its pigments and those of ubiquitous non- N_2 -fixing cyanobacteria. In conjunction with shipboard observations, the lidar information would be extremely helpful in locating regions of high biomass.

Since sizeable efforts are underway in both NASA's Ocean Processes Branch and the National Science Foundation's oceanic program, the Global Biology Research Program will only provide support to these programs as appropriate.

III.3.3 Determining the riverine input of carbon, nitrogen, and phosphorus.

The ocean gains carbon, nitrogen, and phosphorus from riverine fluxes from terrestrial systems. The rate of transfer of nutrients from the land to the oceans depends upon the complex metabolism of the land based biosphere, in both its aerobic and

anaerobic functions. Currently, the flux of nutrients from terrestrial systems, their role in riverine chemistry, and their fate are poorly quantified. The terrestrial component of the Global Biology Research Program must coordinate efforts with the riverine/oceanic component in the design of the most effective sampling strategies.

The major research tasks in this area are to determine the amount of carbon and nutrients coming into rivers from various terrestrial sources under different perturbations, and to determine the subsequent fate of this material. These objectives should be addressed with a two-pronged approach:

1. On several, very carefully selected case study rivers, detailed work should track C, N, and P through the appropriate pathways from the land through the estuaries to the open oceans. This would require local field work, concurrent with remote sensing of basin configuration and particulate and dissolved load. NASA should focus upon the remote sensing, with other agencies supporting the majority of field studies.
2. A monitoring program measuring only discharge to the oceans of C, N, and P should be established on a wider range of representative rivers. This would require automatic sampling and remote sensing, in combination with minimal level ground verification. Such efforts should continue for 3 to 5 years, long enough to establish nonepisodic, normal year-to-year variation.

III.4 To develop and integrate mathematical models to accurately represent the dynamics of the global cycles of carbon, nitrogen, phosphorus, and sulfur, the planetary energy budget, the water cycle, and the oxygen cycle, and process models describing elemental interactions.

Initially, the modelling component of the research program will focus on the major biogeochemical cycles of C, N, S, and P, and some of the key processes that underlie the linkages in these

cycles. Scientifically rigorous global biogeochemical models will be among the primary tools needed to address questions dealing with past, present and future states of the cycles. Further, they may serve to foster program integration. The Research Tasks are:

1. To develop globally aggregated models of the major biogeochemical cycles with simple causalities (Level S-1).
2. To develop globally aggregated models of the major biogeochemical cycles with complex causalities (Level S-2).
3. To develop globally disaggregated models of the major biogeochemical cycles with simple causalities (Level S-3).
4. To develop globally disaggregated models of the major biogeochemical cycles with complex causalities (Level S-4).
5. To develop key process models to clarify elemental interactions and the nature of the subsystem controls.

Modelling of the biogeochemical cycles can be organized into three major areas: Globally Aggregated Models, Globally Disaggregated Models, and Subsystem Process Models. The two categories of global models are further divided into those with simple causalities without elemental interaction and those with complex causalities including elemental interaction (Table III.4.1). When complex causalities are included, one can extend the time-frame to examine such nonsteady-state hypotheses as nitrogen depletion in the oceans leading to a CO₂ shift, or to a climate change, or to nitrogen increases in the ocean. Such hypotheses may or may not require global disaggregation and the associated detailed data sets. Development of globally disaggregate models with simple causalities will be paced by the continued development of new data. The development of more aggregated models with causalities could begin immediately, although the sophistication of included causality will be paced

partly with expanding comprehension of the processes involved (Figure III.4.1).

III.4.1 Models at Levels (S-1) and (S-2).

A first order research task (Figure III.4.2) is an appraisal of existing elemental models and the development of a suite of globally aggregated, simple models for the cycling of N, P, and S. Even at this level, these modelling efforts should attempt to give greater detail to the three major reservoirs--the atmosphere, the terrestrial biota, and the oceans. Carbon, in the terrestrial component of the cycle, has usually been divided into overly simplified compartments in most past modelling efforts. This organization has generally been based either on residence time--"rapid" and "slow" (Bacastow and Keeling)-- or "dead" (Bjorkstrom, 1979). Similarly, oceanic modelling in the carbon cycle was often limited to two or three reservoirs, or to a single eddy-diffusion constant.

These limitations now appear inadequate, even in light of the constraint of low dimensionality for carbon. Similarly, it would prove to be inappropriate for other elements. In fact, concise aggregated models, reflecting greater detail for the terrestrial component of the carbon cycle, are being developed. These models include compartments, adjustable parameters, and fluxes, which facilitate reasonably consistent analyses of many issues concerning the role of terrestrial ecosystems in the carbon cycle (Emanuel et al., 1981). Models at (S-1) and (S-2) levels for the terrestrial component of the biogeochemical cycles should distinguish regions of the earth. Within these regions, the major reservoirs--such as "trees," "ground vegetation," "litter," and "soil carbon"--remain within the spirit of low dimensional global aggregation. Similarly, oceanic modelling should address biogeochemical cycling at greater detail, yet avoid, for the moment, the complexities of two or three dimensional general

circulation models. A more reasonable course at (S-1) and (S-2) levels is the development of what has been termed 1.5 dimensional models of the oceans. These are simply multiple box versions of Keeling and Bolin's original 3-box model. These expanded versions attempt to portray regional characteristics (^{14}C profiles for Atlantic and Pacific oceans). An example of an oceanic model of this kind has been proposed by Bolin (1981). Bolin considers the surface mixed layer, intermediate water, and deep water for the Arctic, Antarctic, Atlantic, Pacific and Indian oceans. One could increase both the horizontal as well as the geographical detail in models of this kind and still retain a reasonable bound on the size of the model. However, elemental interaction within the oceanic system will remain a difficult problem to solve.

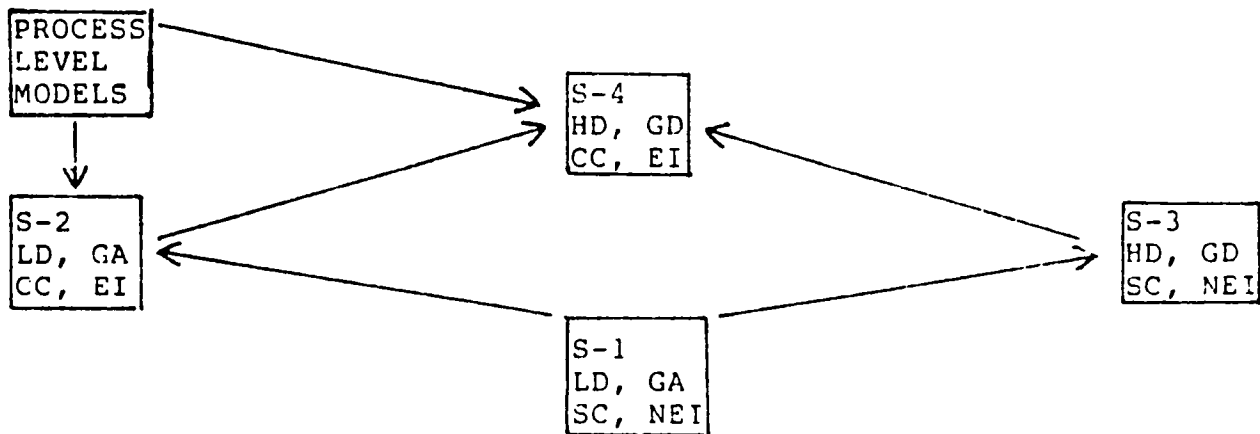
The recommendation that increased detail be incorporated in some of the initial modelling, at level (S-1) of N, P, and S, reflects the second recommendation that the development of low dimensional models (S-2) with more complicated causalities, in particular elemental interactions, be initiated at the earliest stages of the research program (Figure III.4.2).

This recommendation is based upon several assumptions:

1. The development of such models has the greatest likelihood of yielding new scientific insights into the global cycles. For example, of the major elemental cycles, carbon's is best understood, yet the current data and its integration into models suggest the existence of additional significant pathways for carbon fixation, such as nitrogen stimulation of terrestrial ecosystems.
2. The development of such models is cost-effective. They will not require the accumulation of massive data sets or the initiation of large-scale field programs.
3. Successful development of these models will guide the scientific community in its allocation of resources.

FIGURE III.4.1

Relationship among models.



LD -- Low Dimensional
 HD -- High Dimensional
 CA -- Globally Aggregated
 GD -- Globally Disaggregated
 SC -- Simple Causalities
 CC -- Complex Causalities
 NEI -- No Elemental Interaction
 EI -- Elemental Interaction

TABLE III.4.1.

System Level.

S-1: Low dimensional, globally aggregated models for C,N,P, and S
Focus: Cycle-specific, time-horizon 1-1000 years.

Objective: Basic budget, macro-dynamical characteristics without elemental interaction.

S-2: Low dimensional, globally aggregated models for C, N, P, and S with elemental interactions.

Focus: Interaction of cycles over a variety of time horizons (e.g., 1-1000, 10,000-100,000 years).

Objective: For shorter term models the primary objective will be the importance of elemental interaction in systems subject to perturbation including systems where there is direct perturbation of more than one cycle (e.g., fossil fuel burning releases not only carbon but nitrogen and sulfur as well). In longer time-frames, an investigation of nonsteady-state is a prime objective.

S-3: High dimensional, data-rich, globally disaggregated models employing relatively simple (though perhaps numerous) causalities without elemental interaction.

Focus: Regional and subsystem exchanges within the global context with a 1-1000 year time-horizon.

Objectives: There are two overlapping objectives for these models. First, to consider more carefully the details of recent (last 100 years) human perturbations of the C, N, P, and S cycles. Second, to check the consistency of (S-3) models with the models developed within (S-1) and partly within (S-2).

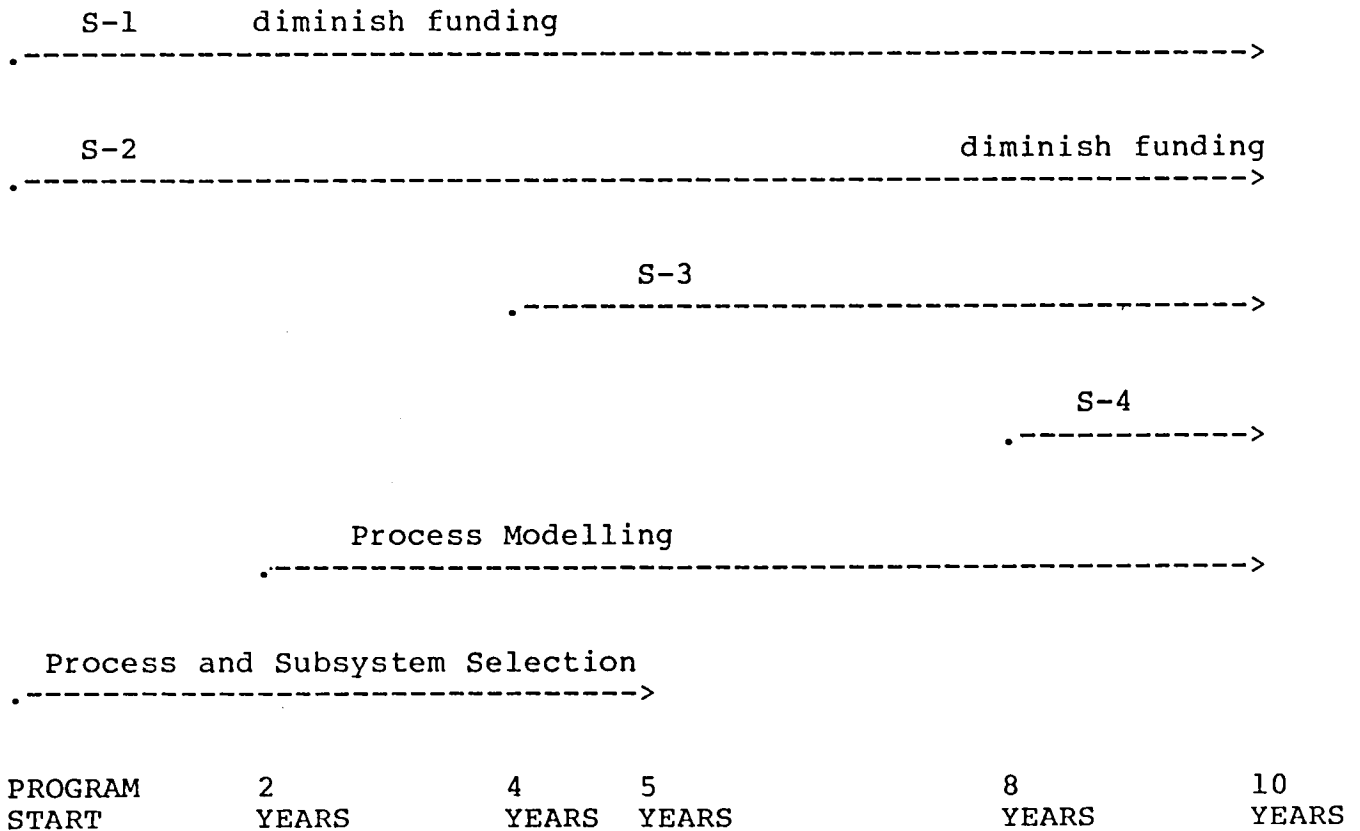
S-4: High dimensional data-rich, globally disaggregated models employing possibly complex causalities including elemental interactions.

Focus. Regional and subsystem exchanges within the global context over a variety of time-frames (1-1000, 10,000-100,000 years).

Objective: An order of magnitude improvement upon our current understanding of the cycles of C, N, P, and S.

Process Level: Certain terrestrial and aquatic ecosystems and oceanic regions may contain features whose clarification would lend major insights when modelling at the system system level (particularly elemental interactions in S-2 and S-4), consequently the program should seek to insure the development of process level models that will significantly clarify important global level dynamics.

FIGURE III.4.2
Indicative Research Schedule (Modelling).



NOTE: Modelling efforts S-3, S-4, and perhaps Process Modelling have as prerequisite new data, and hence there are implicit lines of activity (with start dates) needed to generate this information.

III.4.2 Models at Levels (S-3) and (S-4).

There is a need for an improved data base to develop disaggregated models, even with simple causalities.

Disaggregated models, (S-3) and (S-4), will likely be developed as a linked set of three modules representing the atmosphere, the oceans, and the terrestrial system. Each module will have special data requirements, only some of which are currently perceived.

Disaggregated models with simple causalities (S-3) are focused primarily on questions arising from anthropogenic perturbations. Consequently, these perturbations are important determinants of the structure of the models and the required data. Data acquisition activities and modelling tasks are linked in several ways. First, the data possibilities are a major consideration in selecting the types of causalities and indices for validation. In part, the data possibilities presented in the mid 1980's suggest the use of causalities that integrate a variety of terrestrial ecosystem processes. However, in the atmosphere and, at least, in the geochemical aspect of the oceans, more detailed physical processes may be necessary in (S-3) models.

The terrestrial component of (S-3) level models focus on anthropogenic perturbations and require increased resolution to reflect spatial and temporal heterogeneity. Different terrestrial ecosystems have had different histories, and in a sense, these systems have "memory." Consequently, the responses of systems to perturbations, such as forest clearing or acid rain, will vary significantly among the different types of ecosystems. To elucidate the source or sink role of a particular element in the terrestrial component of the biogeochemical cycles with respect to the atmosphere, models will be developed that are geographically disaggregated and that explicitly treat the

dynamics of elemental cycling for each major type of ecosystem or life zone. A grid 5 degrees by 5 degrees appears to be the appropriate scale. Particular attention will be paid to changes in land use world-wide since this appears to be the major direct terrestrial perturbation.

Initially, for (S-3) level modelling, the program will focus upon change, rather than conduct an inventory. The emphasis on change simplifies the task: it should be easier to measure accurately those areas undergoing change and rates of change than to inventory the entire stock of the earth's vegetation. Such global inventories will be necessary for (S-4) level modelling, since these models will consider the hypotheses of nonsteady-state and hence must address systems not subject to direct human alteration.

Models at the (S-4) level are purely speculative, at present. The goal is to develop (S-4) models that integrate the elemental interactions delineated by the (S-2) models along a temporal process continuum that ranges from the regional level to the global level.

At the (S-3) and (S-4) level for the oceanic component, it is perhaps appropriate to restrict the dimensionality of oceanic models to two. The GEOSECS program has revealed complex patterns of spatial variation that are the combined results of chemistry, biology, and water transport. As mentioned, there are important variations in the distribution of key compounds with latitude and depth (Atlantic, Pacific, Indian), and there are significant differences (as well as similarities) in the patterns among the oceans. A fundamental need will be to model the biogeochemistry in the ocean which reflects this spatial variability. A two-dimensional structure (depth and latitude) should be applied to each major ocean (Atlantic, Pacific, Indian), with tracer transport by advection and turbulent mixing explicitly treated. The resolution in each dimension should be sufficient to permit

reasonable comparisons of predicted distributions with contour plots, or their representations, of extensive data from GEOSECS and Transient Tracers sampling programs. The redistribution of carbon isotopes by marine biota will be simulated, and provision will be made to consider parallel movement of oxygen, phosphorus, and nitrogen. The objective is an accurate estimate of the gross and net fluxes of C, N, P, and S between the oceans and the atmosphere. It should be possible to use a general circulation model of the ocean (cf. Bryan, 1975) to determine the major feature of the oceanic flow patterns and turbulent transfer processes. These general circulation features should be consistent with the external forcing of the oceans; e.g., differential heating and wind stress at the sea surface. Some approximate results are available, but the dynamics of the oceans are difficult to capture in global models because of the important role played by rather small-scale features.

The primary difference between modelling the ocean at the (S-3) level versus the (S-4) level is that (S-4) models will include elemental interactions and the effects of climate on physical processes (currents). The latter is necessary in order to consider more extended time-frames.

III.4.3 Models at the Process Level.

To understand the biosphere and the ways humans may be changing the natural biogeochemical cycles, the key physical, chemical and biological processes that govern these cycles need to be described quantitatively. This, in turn, requires the study of small scale (in both time and space) systems whose important, but detailed, processes cannot be included directly in global models. As a consequence, the Program will identify particular small-scale systems whose dynamics, if clarified, would be important in addressing (S-2) and (S-4) global models.

IV. MANAGEMENT OPERATING PLAN

IV.1. Ten Year Plan and Objectives

The major research issue-areas described (Sect.II) and task descriptions (Sect.III) cover aspects of the Program for the next ten years. In general, four research issue-areas are emphasized:

- (1) Pathways and rates of exchange of C, N, S, and P, to and from terrestrial ecosystems.
- (2) Anaerobic processes and associated biological sources and sinks of atmospheric trace gases.
- (3) Biogeochemical fluxes of C, N, S, and P, to and from the world's oceans directly modulated by biological processes.
- (4) Integration of biogeochemical fluxes into macro-scale global models and meso-scale process models.

IV.1.1. Schedule and Milestones

The ten year program master schedule, reflecting major research objectives and tasks, shows dates of expected accomplishments (Fig. IV.1.1.). Accomplishments indicated by triangles refer to either the establishment of first order vegetation maps or an estimation of particular gas fluxes in a specific representative ecosystem. The research program is intended to continue over a longer time frame than indicated. Continual refinement of various measures is anticipated. The Program schedule covers seven major task categories:

- 1) Data Base Management System (DBMS)
[Research Data Base]
- 2) Biospheric Model Development
- 3) Global Vegetation Maps
- 4) Global Land Use Change Maps
- 5) Global Biogenic Gas Flux Characterizations
- 6) Stratified Sampling Plan
- 7) in situ Measurements

IV.2. Management Structure

IV.2.1. Program Organization

The Program in Global Biology is expected to continue as a modestly-sized research program over the next ten years. Since the Program thrust is to understand the influence of biological processes on global dynamics, a holistic approach to the system that exists on Earth is required. This approach requires convergent technology and research activities by a multidisciplinary group of scientists. Many of these activities will proceed in other programs, but careful planning and coordination of research activities will produce correlative data, yielding insight into the fundamental aspects of the system that supports life.

The Global Biology Program Office is contained within the Research and Technology Branch of The Life Science Division of the Office of Space Science and Applications (Figure IV.2.2.1.). Within the Program Office, the Discipline Scientist for Global Biology serves as Program Manager.

The Program Manager will be responsible for planning, budgeting, grant monitoring, program balance, review and approval of Research and Technology Operating Plans (RTOP's), interdivision coordination of activities pertinent to the Program, interagency coordination of activities pertinent to the Program, and peer review and approval of proposals. All research approvals act as recommendations to the Director of the Life Science Division and are therefore subject to further approval.

Details of Field Center representation and corresponding management responsibilities will be determined as the Program progresses. It is hoped that Center managers will be designated for the responsibility of coordinating Center RTOP submissions and individual tasks, in accordance with the Program Office.

IV.2.2. Program Coordination

A system analysis approach in understanding the fundamental aspects of the biosphere requires a multidisciplinary team of scientists and carefully planned and coordinated research activities. The primary responsibility of coordination will essentially be a management function.

IV.2.2.1. NASA Interdivision Cooperation

Since many components of a biospheric study already exist throughout NASA, the coordination of research activities between related programs will provide complementarity for aspects of both funding and integration of data. These other programs exist primarily in two divisions within the Office of Space Science and Applications: Environmental Observations, and Earth and Planetary Exploration (see NASA Organization Chart, Figure IV.2.2.1.).

Within the Division of Environmental Observations (EE), the following Program Offices are relevant to Global Biology: Oceanic Processes, Tropospheric Air Quality, Upper Atmospheric Research, and Climate.

The Division of Earth and Planetary Exploration (EL) contains the Program Offices of Renewable and Non-renewable Resources. These offices primarily manage remote sensing programs operative on land.

The facilitation of program coordination and cooperation will require an organizational structure that specifies periodic meetings between Division Directors for budget considerations, and between Program Managers for considerations of RTOP submissions, proposal co-funding, and general research opportunities. General guidance may be recieved from an interdivision Science Working Group (SWG) that includes NASA personnel and research scientists, who can provide advice on needed research and program direction.(Figure IV.2.2.1a).

IV.4.2.2.2. Interagency Coordination

Interagency relations will be the responsibility of Program Management. Periodic meetings between related program offices will be planned to coordinate mutually beneficial opportunities of research and for information transfer.

IV.4.2.2.3. Data Integration

The integration of data will occur mainly through modeling efforts facilitated through the establishment of a research data base (DBMS). However, since the research data base will take some time to establish, annual Principal Investigators meetings will occur to allow investigators the opportunity to report and discuss their data.

Figure IV.2.2.1. Office of Space Science and Applications

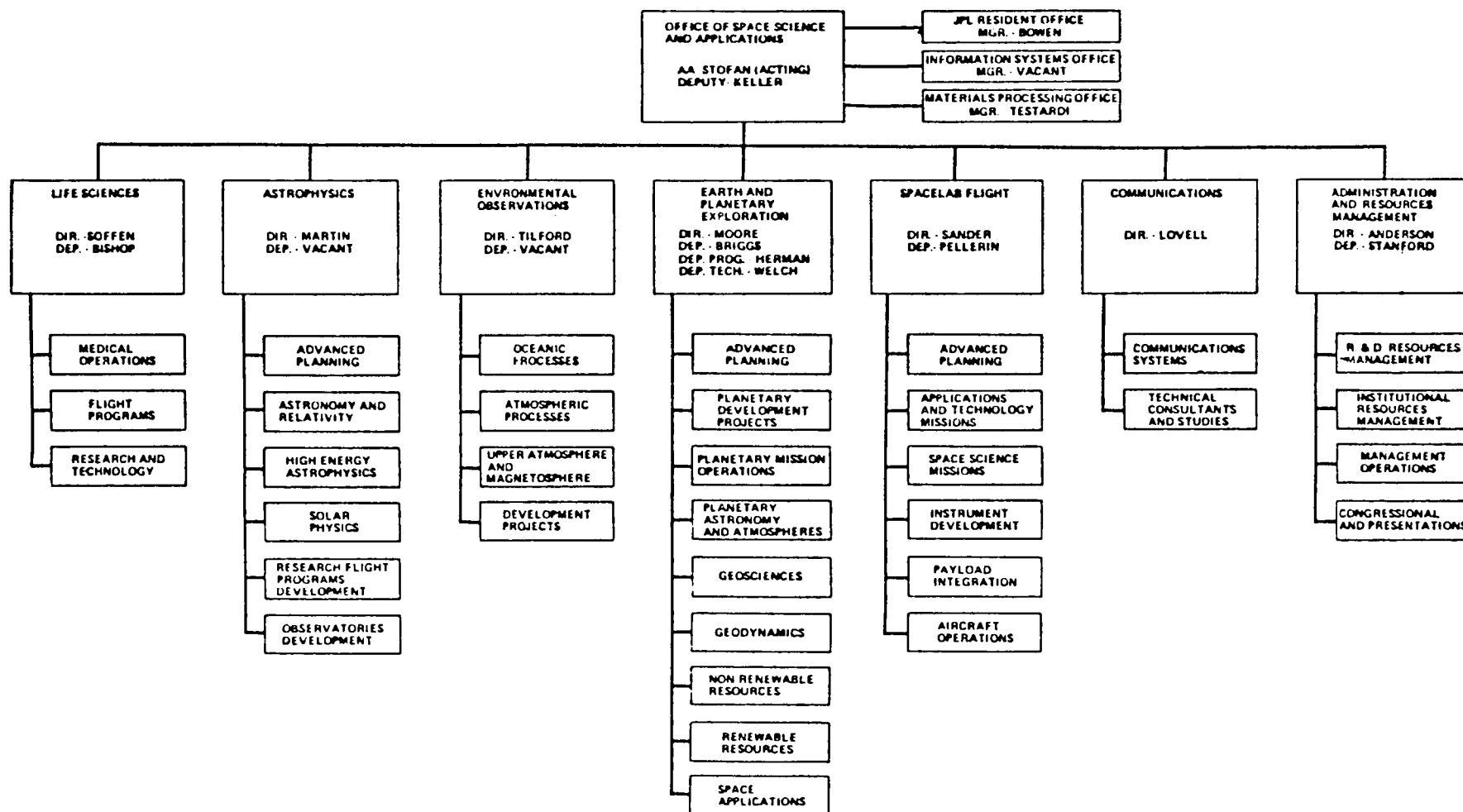


Figure IV.1.1.

GLOBAL BIOLOGY MASTER SCHEDULE

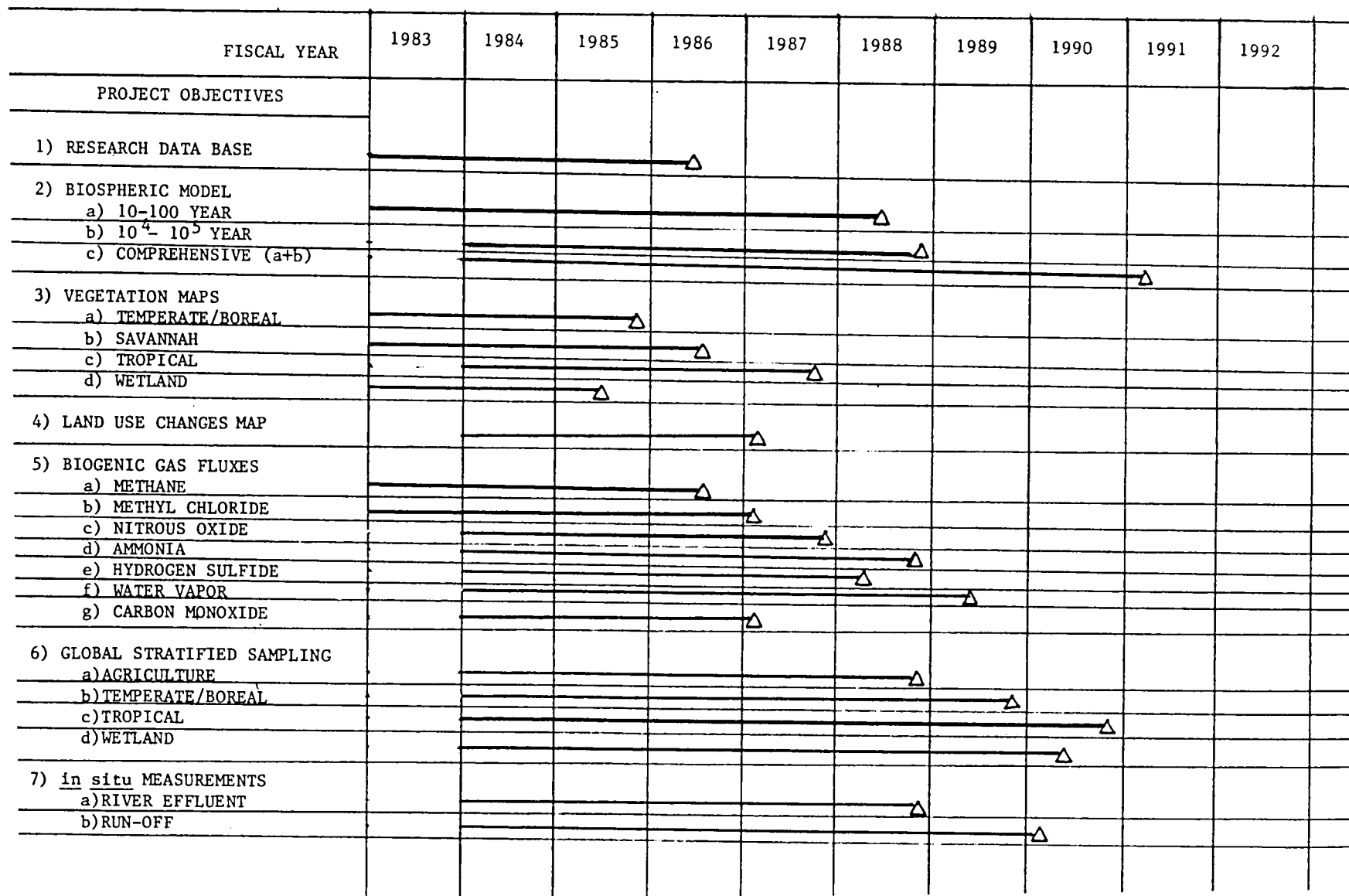
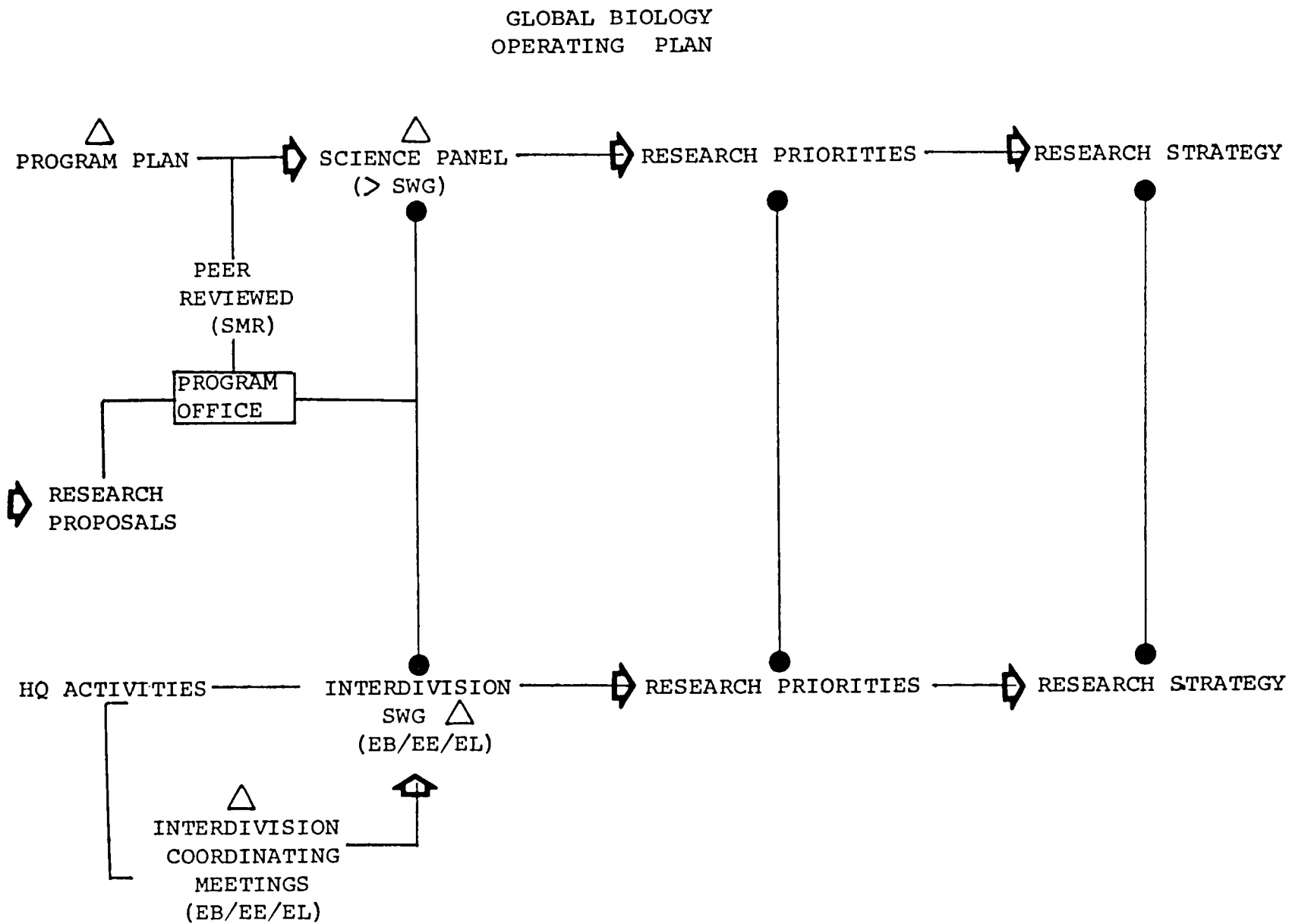


Figure IV.2.2.1a.



IV.3. Research Implementation

IV.3.1. Project Acquisition

IV.3.1.1. Field Center RTOPs and Proposals

Annual research plans for the Program in Global Biology are developed according to submissions from the Field Centers by their Research and Technology Operating Plan (RTOP). The Centers submit their RTOPs according to the present RTOP structure:

RTOP Number	Title
199-30-1X	Modelling
199-30-2X	Atmosphere Biosphere Interaction
199-30-3X	Terrestrial Ecology
199-30-4X	Ocean Ecology
199-30-5X	Instrument Development

The following sections briefly describe each RTOP, however, details of task descriptions or research issues can be found in other sections within this Program Plan (see Table of Contents):

Modelling: This RTOP addresses the synthesis and integration of existing and developing data sets by combining climatic, oceanic, terrestrial, and biogeochemical cycling models. The formulation of a comprehensive mathematical model(s)

describing the fundamental interaction of the biota with the Earth's chemical/physical environment serves to delineate data gaps in our understanding, thereby designating needed research and general Program direction. Included in this RTOP are those tasks designed to address the identification, archival, and/or processing of existing or developing data, to eventually establish a research data base that serves the needs of both modelers and experimentalists.

Atmosphere/Biosphere Interaction: This RTOP addresses the characterization of biologically mediated atmospheric gas fluxes--the identification of biological sources and sinks of atmospheric gases and the elucidation of those factors that influence biogenic gas flux magnitude. Those research projects dealing with the influence of biological processes on climate, atmospheric composition and radiative transfer, and biogeochemical cycling, are relevant to this Program area.

Terrestrial Biology: This RTOP addresses the use of existing remote sensing data coupled with ground-based research to improve our estimates of biomass size and distribution, rates of change, and terrestrial productivity. Coupled remote sensing/ ground-based data should also improve our ability to characterize the rates and pathways of nutrient transfer to and from terrestrial ecosystems. Other research topics relevant to this Program area include topics related to land-sea interaction: e.g., the determination of river effluent chemical composition related to nutrient transfer impacts on estuarine and ocean productivity, and run-off composition related to land use changes.

Oceanic Biology: This RTOP addresses the determination of ocean productivity, biomass size and distribution, and the characterization of the influence of biological processes on ocean dynamics.

Instrument Development: This RTOP addresses the design of instruments that will provide necessary technology for increasing resolution or sensitivity of crucial measurements, either by instrument adaptation or development, as specified by the Program research areas.

Technical and funding guidelines are sent to the Centers yearly, in February, by the Program Office. Center plans are reviewed with the Program Office in March and April before formal submissions are accepted. Center investigators, included in RTOP submissions where new research is indicated and deemed relevant by the Program Manager, must then submit formal proposals for peer review. Following a program funding formulation of research projects for the fiscal year, a presentation is made to the Director of Life Sciences for approval. Once approval has been made by the Director, a formal presentation is made to the Assistant Associate Administrator of the Office of Space Sciences and Applications. If clearance is given, funding allocations procede for the new fiscal year, beginning on October 1, for those projects that have had formal submission of proposals with an acceptable peer review.

IV.3.1.2. University/Institute Unsolicited Proposals

Unsolicited proposals from the scientific community outside of NASA can be submitted at any time. NASA policies and procedures for unsolicited proposals are described in the University Affairs Office brochure, "The NASA-University Program: A Guide to Policies and Procedures". Relevant proposals received by the program office are subjected to peer review for determination of science merit. Those proposals with an acceptable science merit rating are then

considered for funding by the Program Manager. Funding decisions are based on available funds, coordination with on-going research, and consistency with the overall Program Plan. However, to save time and effort, it is strongly recommended that interested science personnel submit a pre-proposal (concept, approach, and budget) or contact the Program Manager, directly, for informal consideration before submitting a research proposal.

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APPENDIX

SUPPORT DOCUMENTS FOR GLOBAL BIOLOGY (SELECTED)

Botkin, D., editor. Life from a planetary perspective: Fundamental issues in global ecology; NASA Life Sciences Division Workshop report on Global Ecology; November, 1980.

Botkin, D., editor. Life from a planetary perspective: scientific strategies for a program in global biology; NASA Life Sciences Division Workshop report on Global Ecology; June, 1982.

Dastoor, M.; Margulis, L.; and Nealson, K., editors. Interaction of the biota with the atmosphere and sediments; NASA Life Sciences Division Workshop report on Global Ecology; October, 1979.

National Academy of Sciences. Origin and evolution of life-implications for the planets: A scientific strategy for the 1980's. NAS Space Science Board Subcommittee Report (Committee on Planetary Biology and Chemical Evolution); National Academy Press, Washington, D.C.: 1981.

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National Academy of Sciences. Two special issues in satellite oceanography: ocean dynamics and biological oceanography. Ocean Science Board, National Academy Press, Washington, D.C.: 1982.

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16. Abstract <p>Life depends on the cycling of material through different energy states largely a consequence of biogeochemical cycling. Biological processes play a dominant role in these cycles transforming and transferring much of this material throughout the biosphere. NASA's Global Biology Research Program is dedicated to achieving a greater understanding of planetary biological processes as revealed by the interaction of the biota and the environment.</p> <p>This document is the product of the Global Biology Science Working Group which was convened to discuss and formulate NASA's role in Global Biology. The report is not intended to be a comprehensive review of global biogeochemistry. Its purpose is to inform interested agencies and individuals of the rationale, scope, research strategy, and research priorities of the Program.</p>					
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